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POTENCY OF INFORMATION TECHNOLOGIES IN SENSOR SYSTEMS

Hans-Rolf Tränkler, Olfa Kanoun

Institute for Measurement and Automation,
University of the Bundeswehr Munich,

Abstract – Developments of sensor technologies rely on the permanent technical progress in the fields of manufacturing and information technologies. The choice of a novel technology for a certain sensor system is not necessarily associated with improved sensor features. An optimal performance to cost ratio is in general only obtainable by the choice of suitable combinations of both manufacturing technology and signal processing.

This paper gives an overview about the role of information technology in sensor technologies involving sensor design, signal processing and sensor communication. Special care is dedicated to sophisticated digital signal processing methods for smart sensors and multi sensor systems permitting to improve measurement quality. The paper is concluded with expected future developments in the field of sensor technology.

Keywords Design of Sensor Systems, Signal Processing, Future Trends

1. INTRODUCTION

Most significant developments in engineering result from developments in more than one scientific field. Combining solutions from different fields enables synergetic effects, which result in particularly outstanding solutions. This can be observed in many fields where interdisciplinary work is required.

In sensor technology developments are particularly driven by the permanent technical progress in the fields of sensor manufacturing technology and information technology. Both fields are thereby in a close and interlocked interaction in which they are dependent on one another. In other terms there is a symbiosis taking place between both fields, which is demanded among others because of the generally shorter becoming product life cycles.

Microsystem technology e.g. is itself a concrete comprehensible example for this symbiosis. It integrates sensors mechanical structures, multifunctional materials and microcircuits for signal processing on the same substrate. Using microsystem technology leads to a lot of advantages with regard to the application, such as realizing low-cost solutions, higher reliability, smaller size or higher power density.

An optimal performance to cost ratio is in general only obtainable by the choice of suitable combinations of both manufacturing technology and signal processing (figure 1). The choice of a novel technology for a certain sensor or sensor system is not necessarily associated with improved sensor features such as in sensitivity to influence factors or linearity. Manufacturing technology is based on physical and chemical processes, which are themselves affected by different effects

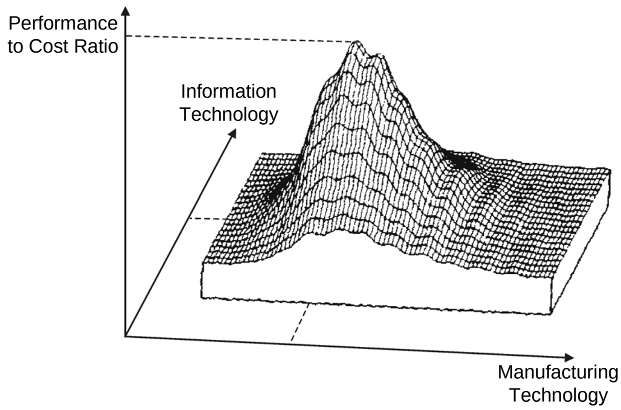

Figure 1. Performance of smart sensor systems

Sensor features are generally just known at the end of the production process. The more process steps are used the more difficult are technological measures for avoiding undesired effects in sensor signals. It is therefore often indispensable to make use of a sophisticated signal processing avoiding the relevant occurring undesirable effects in each individual case.

2. INFORMATION TECHNOLOGY IN SENSOR TECHNOLOGIES

In the field of information technology a significant upturn has been taking place in the last decades. The role of information technology is since then increasing in the field of sensor technology. It involves sensor design, signal processing and communication (figure 2).

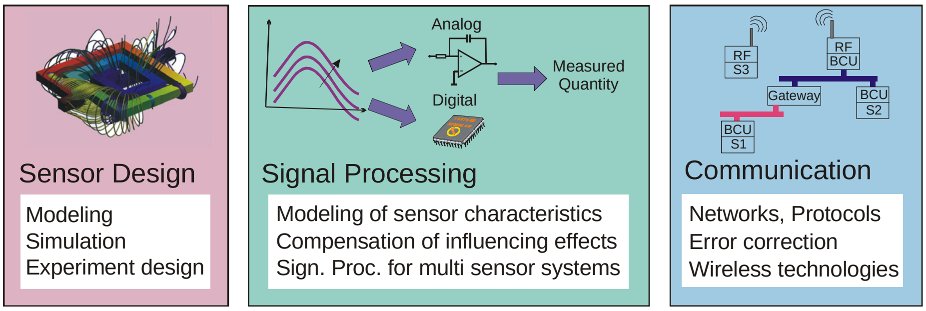

Figure 2. Important role of information technology

During sensor design simulation and modelling techniques contribute significantly to reduce development costs. This is of a big importance because of the shorter and shorter becoming product time-to-market.

In signal processing digital information technologies are increasingly used in order to eliminate undesired effects influencing the sensor signal and leading to supplementary uncertainties.

Communication interfaces are nowadays an inherent part of many sensors. They allow to transmit the more or less processed sensor signal to higher-level systems and have therefore a big importance for the integration of sensors in a wide range of applications, such as industrial process monitoring, smart home instrumentation, environmental oversight, safety and security.

3. SENSOR DESIGN

Developing the sensor element for a certain sensor principle is a long iterative process. For sensor design a lot of trials are needed in order to choose the right materials, components and dimensions [1]. The use of information technologies such as simulation and modeling techniques can significantly contribute to increase the efficiency of the design and optimization process of sensors. The ideal aim thereby is to realize a successful system design if possible at the first fabrication attempt, so that the sensor time-to-market can be shortened.

The reachable results by simulations are generally beyond them, which can be reached through measurements only. Some cases of operation, which occur accidentally or are only realizable with difficulties, can be precisely investigated. Statistical characteristics describing the behavior of a sensor system can be easily calculated. In some fields with a high market competition such as automobile industries, the time-to-market is more important than development expenditure. Also simulations of experiments are carried out in order to concurrently prepare the signal processing with the design of sensor systems. In other fields, such as fire early detection, simulation of experiments helps to reduce the expenditure for the investigation of sensor systems [2]. The design of fire detection algorithms is an iterative process that requires continual performance estimation. The realization of required test fires and disturbing events is expensive. Through modeling of the sensor responses during experiments, a useful simulation environment was developed [2].

4. SIGNAL PROCESSING FOR SINGLE SENSORS

Signal processing provides an opportunity to improve sensor properties in spite of the abundance of influencing effects, such as manufacturing variance, hysteresis, drift, aging and cross sensitivity, which are unavoidable and represent a systematically source of uncertainty. The influence of a certain effect on the sensor signal is dependent on the type of the error caused (additive or multiplicative) and on the sensor structure (chain, parallel or closed loop). In sensors with a chain structure, even additive errors result in a higher nonlinear error [3]. A closed loop structure could perhaps reduce but hardly eliminate errors. A parallel structure, which is a classical measure in information technologies for in-phase suppression, is able to reduce additive effects. If the effect on both components is equal, like in the differential principle or if one component is not affected at all, like in the reference principle, the effect could be eliminated.

Although it is principally possible to reduce or eliminate some effects with technological measures, it is often carried out by signal processing because of cost optimization. By means of low-cost analog-digital converters, signal processing is increasingly shifted from the higher system level to the sensor level. The diverse facilities in the field of digital signal processing involve new approaches for the improvement of sensor properties.

For instance in some cases the correction of the effect of certain influence factors like temperature is indispensable in order to reduce measurement errors. Analog methods can be carried out trimming some circuit elements after calibration processes. The influences of the individual circuit element is generally related to each other, so that the reached correction quality is strongly dependent on the choice of the order of elements during the trimming process. Furthermore nonlinear signals can not be easily treated and aging processes couldn't be considered. A remedy performs a digital compensation of influence factors such as the basis function procedure [3]. The basic idea thereby is that the sensor characteristic may be shifted or shrink under influence of a quantity like temperature. But it doesn't change its global structure a lot. This procedure consists of transforming the sensor characteristics at different values of the influencing quantity to only one characteristic at reference conditions. After separation between the signal and the influence factor, the measured quantity can be determined from the reference characteristic called basis function.

Many sensor signals are subject to aging processes due to the degradation of the used materials which leads to a change of their electrical properties. Aging processes can considerably affect the sensor static properties, such as the sensitivity or the zero point. These effects can be corrected offline through calibration processes.

If aging effects could be detected electrically, online self-calibration processes can be implemented realizing a considerable reduction of maintenance costs.

For example the aging process of electrochemical gas sensors is correlated with the reduction of the active area, which can be measured by means of impedance measurement (figure 3). Therefore by simultaneous impedance measurements of the electrochemical cell, aging effects can be compensated during operation.

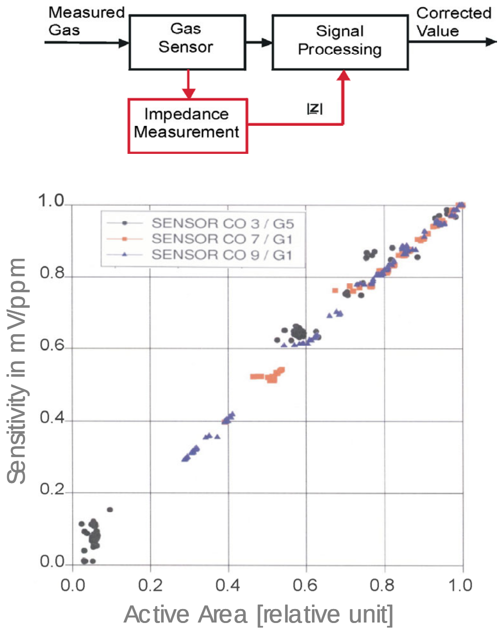

Figure 3. Correction of aging effects for electrochemical gas sensors [4]

Sensor signals affected with a hysteresis effect are dependent on the signal history. The relationship between sensor input and output is in this case not unique. The correction of this effect is not a simple task. Different models for the digital correction were investigated in [5]. The model by Preisach-Krasnosell'skii has some advantages for sensor technology because it allows considering a long signal history. The hysteresis is modeled by a parallel circuitry of weighted hysteresis operators with different up and down thresholds. Figure 4 shows a graphical illustration of the Preisach-Krasnosell'skii model. The filled points in the triangles correspond to the hysteresis operators switched on. The effects of the rising and sinking x in the triangle can be shown in Figure 4. The history of the signal results as steps in the triangle graphic.

For an easier implementation of this method the Preisach-Krasnosell'skii model was so modified, that only the step function and not the whole surface of switched operators is considered [5]. The calculation process become thereby faster and less memory intensive.

The modeling of sensor characteristics is useful for an extensive signal processing which simultaneously considers many occurring effects. For example gas sensors based on metal oxides are low priced but show a low selectivity and unsatisfying longtime properties.

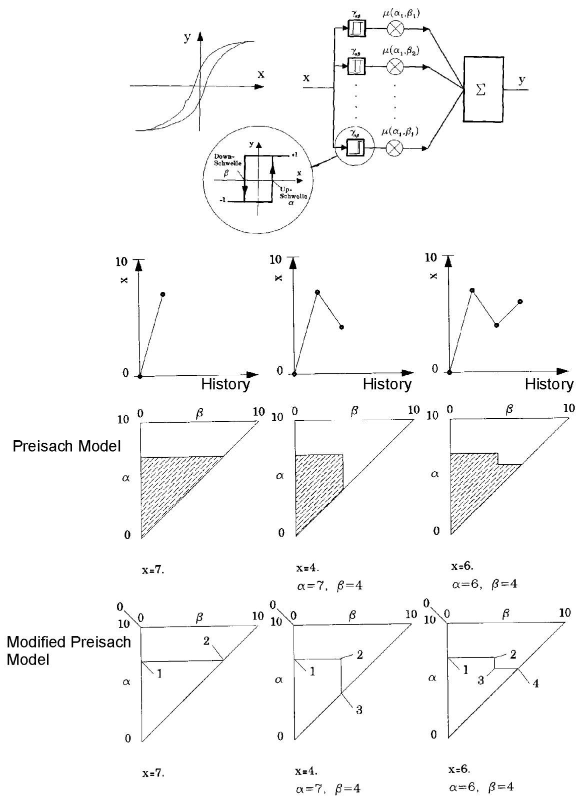

Figure 4. Graphical illustration of the Preisach-Krasnosell'skii model [5]

The precision of the gas concentration measurement could be improved through an accurate sensor characteristic modeling and corresponding signal processing.

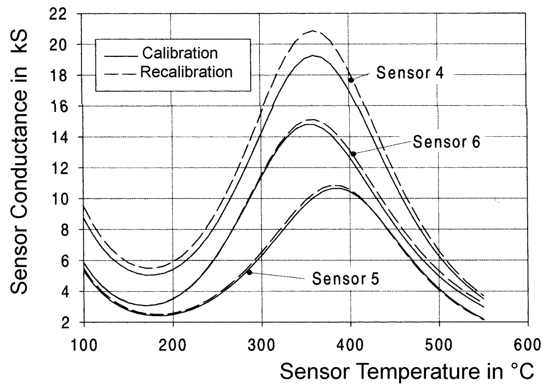

Figure 5. Model for the zero point calibration of semiconductor gas sensors [9]

For instance, using the model by Horn (1) the temperature dependence of metal-oxide sensors could be taken into account, so that an accurate calculation of the gas concentration could be carried out [6].

$$G = g \cdot \frac{B + A \cdot x_g}{1 + A \cdot x_g} \qquad (1)$$

x_g: Gas concentration, G: Conductance, A, B: Temperature dependent parameters, g: Conductance referring to the charge carrier number

Additionally moisture strongly affects the sensor properties. With a physically and chemically based model both effects could be simultaneously described (figure 5). The model complexity level and especially the number of model parameter used permits its application for the compensation of the zero point of the sensor. This is the sensor conductance in absence of detectable gases.

5. SIGNAL PROCESSING FOR MULTI-SENSOR SYSTEMS

The use of multi-sensor systems is becoming more important in widespread application fields. Their applications reach from the monitoring and automation of manufacturing processes to robotics, automotive applications, smart home, process control, environmental engineering, biotechnology and life sciences. In general, single sensors can only provide partial information on the state of the environment while multi-sensor systems combine related data from multiple similar and/or different sensors.

Information technologies such as data fusion techniques have a key role in the signal processing. Typical methods are: Statistical decisions, average value methods, Kalman-filter for the fusion of sensor rough data, fuzzy logic for qualitative formulated problems and neural networks for problems, where the expected behavior could be trained using a set of characterizing examples.

The design of multi sensor systems includes the choice of sensors and processes of multi-sensor data fusion with the aim to ensure the right calculation of the required measurement values or decisions. For instance, for presence detection, ultrasonic detectors have a high sensitivity to noise, thermal induced air turbulence and movements of hanging curtains and plants. Microwave detectors may detect an object motion outsides the observed room or be mislead by other electromagnetic fields. The combination of both detectors and the use of adapted signal processing achieves a better detection reliability, because of the different ways in which both detectors are affected by disturbances [7].

In hazard warning systems such as in the free-range protection by video signal evaluation or in the fire early detection, multi-sensor systems are indispensable because of the high level of reliability required. For instance, in early fire detection, sensor arrays including optical scattered light detectors and gas sensors improve reliability and reduce reaction time because gases diffuse more rapidly than smoke particles during the initial fire phase [2]. In this case the signal processing should be able to discriminate between fire, not-fire and disturbing event situations by identifying fire signatures from measured sensor responses [2]. For signal processing a feature extraction procedure taking care of the specific sensor features followed by a pattern recognition procedure is necessary. A realized multi-sensor system reached significant improvements by several test fires (European Norm EN 54, and cable fire) compared with commercial optical detectors.

6. SENSOR COMMUNICATION

Communication interfaces are nowadays an inherent part of most sensors. Information technology plays in this case a big role for integration of sensors in a wide range of applications, such as industrial process monitoring, smart home instrumentation (s. figure 6), environmental oversight, safety and security. Digital sensor communication is used in process control or in data acquisition. The main advantages are the reduced wiring expenditure (cable costs), the easy installation and configuration and the disturbance-free signal transmission over long distances.

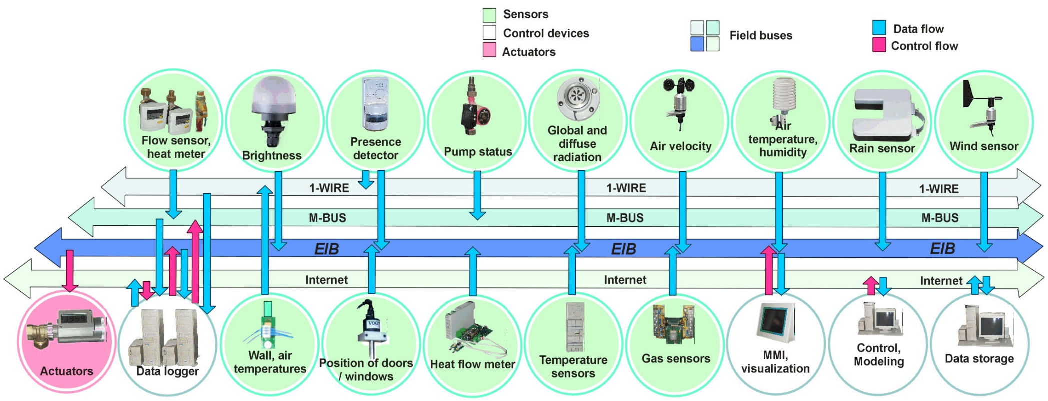

Figure 6. Communication in smart buildings [11]

A sensor usually imposes very moderate requirements on the communication rate and hardware complexity. A serial bus system is the most efficient realization [12]. Nevertheless many criteria must be considered when selecting a field bus system. Various requirements must be fulfilled when optimizing the bus system for a specific task. These include multi-vendor support, electrical noise immunity, and determinism. Short and constant cycle times, a highly efficient transmission protocol, and easy operation and diagnostics are also very important.

In extensive systems several communication networks can be used in order to connect a big amount of participants or because of different tasks (figure 6). For this purpose networks of the same communication bus can be connected with bridges. Different communication networks need gateways.

Wireless communication is increasingly gaining importance [13]. It has become reliable and cheap through the availability of the techniques e.g. used in consumer mobile applications. It involves useful advantages for many applications such as applications in which long distances are to be bridged or a big number of distributed components is necessary. They involve many advantages concerning retrofitting of existent systems. An infrared communication can be used for a high transmission rate but over only short distances less than 2 meters. A permanent inter-visibility (LOS: Line-of-sight) between sensor and basis station is required. Therefore wireless radio frequency communication is gaining more acceptance in many applications.

7. FUTURE TRENDS IN SENSOR TECHNOLOGY

The development trends in sensor technology result from market-economical aspects, general customer requests and the requirements for an implementation in a certain applications. Costs decrease, improvements of accuracy, reliability and speed are to be realized using improved measurement methods, novel manufacturing technologies and sophisticated signal processing techniques. The role of information technology will continue to grow in all these fields. Information technology is thereby simultaneously a development and prediction tool, a calculator of the useful information and an indispensable infrastructure for sensor integration in higher-level systems.

The application field of sensor technology is becoming wider. Sensor systems will intrude continuously the consumer sector. Thereby, we can observe that contact less sensor technology is upcoming. Especially optical sensor technologies are gaining importance in a wide application field including gas concentration measurements, fire detection and video sensors (biometry).

Harsh environments are often unavoidable in a variety of engineering applications. They may involve extreme physical conditions, such as high-temperature, high-pressure, corrosion, toxicity, electromagnetic interference, and high energy radiation. Conventional sensors are often difficult to apply so that special sensors should be developed. Basic materials, bonding technologies and packaging should be correctly considered. For example new materials such as silicon carbide can be used together with the right bonding materials at temperatures until 870°C [10]. Electronic packaging should also fulfill more than a protective function. Packaging concepts for harsh environments should fulfill high reliability and thermal management at reasonable costs. For high temperature applications the lowest possible thermal resistance throughout the whole assembly should be realized.

7.1 Trends in Sensor Design and Manufacturing Technologies

In sensor design, simulation techniques will furthermore play an important role for the improvement of sensor design. Simulation techniques of well-known technologies become in the meantime established, so that the combination of simulation and experimental tests converges faster and faster.

The trend to miniaturization will continue to grow, supported by the continued developments of micro electromechanical systems technologies and nano technologies. Miniaturization is the key for increasing reliability, reducing power consumption and minimizing costs.

Important developments are taking place in near future in the field of micro technologies. The eminent properties of silicon material, such as the freedom of hysteresis errors, let silicon micro machining be one of the most significant micro technologies for sensors and sensor systems [1].

For the integration of sensors and actuators in microsystems many functional or protection layers are required. Protection layers are generally slight layer, which are used against corrosion, wear and oxidation. Functional layers are used e.g. for friction reduction, contacting or adaptation. For example in the case of gas sensors, selective functional layers are of big importance for increasing selectivity.

The requirements for microsystems are increasingly becoming complicated, so that customized multifunctional layers combining several effects will be in the focus of future developments. Particularly nano structured multifunctional multi plies layers and nano crystal layers are of a big importance [8]. Using a suitable combination of different slight layers or different structures and properties of nano crystals customized multifunctional layers can be developed for different requirements.

Devices manufactured in HARMST technologies [9], such as LIGA (Lithography-Galvanic) processes, special photolithography and plasma etching, achieve a high aspect ratio. This means, that the structure height is high relative to the minimal lateral dimension of the whole structure. The so called Bosch process (DRIE: Deep Reactive Ion Etching) can be used for manufacturing silicon micro structure [9]. HARMST technologies will subject of important developments because of the considerable advantages it involves for the performance of the micro structures such as sensitivity, displacement, mechanical robustness and reduced noise.

7.2 Trends in Signal Processing

A model based signal processing can significantly improve many sensor properties. Former difficulties with calculation times or analog to digital conversions are no more relevant.

For many sensors more accurate physically and mathematically based models should be developed. The progress in the field of information technology can help to understand complicated dependencies and to describe them quantified with the right functions

An important trend will be the reinforced development of sensor systems with online self-test or self-calibration (figure 7).

Using adequate analog and digital signal processing and an appropriate a-priori knowledge about sensor behavior self or built-in tests can be implemented. Incorporating this functionality in signal processing together with the sensor design will prove to be critical to reducing the overall, final costs and increasing system reliability.

The trend towards built-in self-test or self-calibration leads up to the design of totally calibration-free sensor systems. The “a priori”-knowledge about the sensor behavior is in this case a characteristic model having a suitable mathematical structure and including the measured quantity as a parameter. Inverse identification problems could online calculate the measured quantity together with all unknown parameters. The realization of this principle in the case of p-n temperature measurement can be considered as a pattern for further progresses in measurement technology [11].

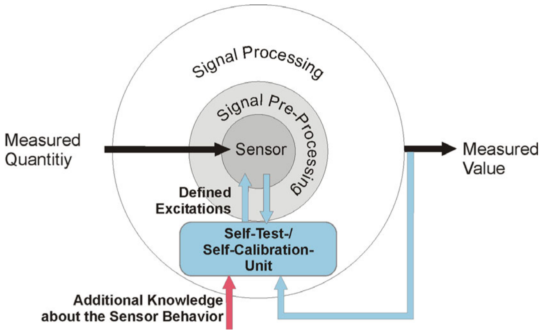

Figure 7. Sensor with self-test or self-calibration

Slight or non invasive measurement methods, such as impedance spectroscopy will be increasingly used in future. The principle of this measurement technique is to measure impedance at a device using currents or voltages at different frequencies. The evaluation of the measured data can be carried out by mathematical methods or by means of an equivalent circuit (figure 8).

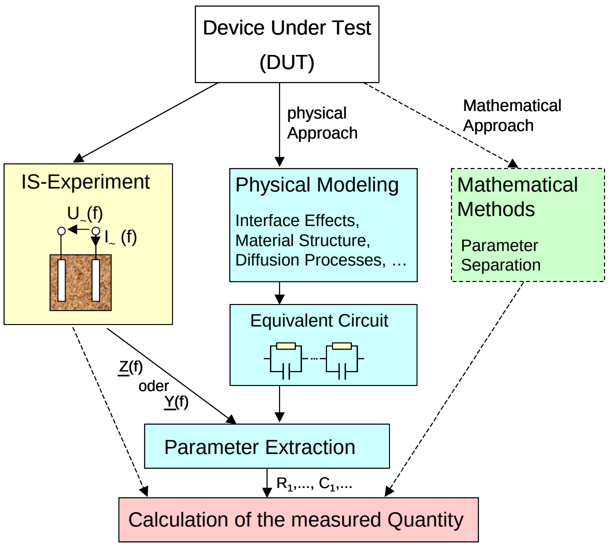

Figure 8. Impedance spectroscopy methods

The powerfulness of this method rely on of the possibility to get information in the three dimensions: real part of impedance, imaginary part of impedance and frequency. This big amount of data can be used in order to measure a lot of quantities concerning material properties, material interfaces, geometrical structures and different diffusion processes.

9. OUTLOOK

Automation and control of processes can not be better than the information delivered by the sensor. Sensors and sensor systems are therefore decisive components, which can be a measure of quality, reliability and economic efficiency of technical products and automated systems. Developments of sensor systems are important for the technical progress in wide spread fields of applications. The support of progress in this field is more necessary then ever. The profitability will generally go up because of the increasing number of units used and if combined modular solutions are realized.

For the development of new sensors, an interdisciplinary work of key competence from different fields is indispensable. Future sensor systems will be designed in an integrated design processes including not only the technological aspects, but also the design of the specific manufacturing step and the required signal processing.

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Authors:
Prof. Dr.-Ing. Hans-Rolf Tränkler, Institute for Measurement and Automation, University of the Bundeswehr Munich,
85577 Neubiberg, Germany
Tel.: 089-6004-3740, Fax: -2557,
Email: ima@UniBw-Muenchen.de

Dr.-Ing. Olfa Kanoun, Institute for Measurement and Automation, University of the Bundeswehr Munich,
85577 Neubiberg, Germany
Tel.: 089-6004-3954, Fax: -2557,
Email: Olfa.Kanoun@UniBw-Muenchen.de