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An approach enabling Accuracy-as-a-Service for resistance-based sensors using intelligent Digital Twins

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Abstract

A key performance indicator for sensors in production systems is their accuracy. In order to respond to the flexible requirements posed to production systems, there are currently two possibilities to realize the needed accuracy. Either the sensors can be changed frequently, so that the lowest still sufficient accuracy can always be achieved or the production system can be equipped directly with highly accurate sensors. These two options come with high costs, originating from the manual effort and the proportionality of accuracy and cost for most of the commonly used sensors. Industrially used resistance-based sensors such as pressure, force or temperature sensors represent a special case here, because their inaccuracy traces back to few major sources. To eliminate some of these sources or to decrease their impacts, instance-specific characteristics are used in an accuracy model provided by an intelligent Digital Twin. Using varying accuracy models provides different levels of accuracy. The presented concept provides the needed accuracy permanently or as a service for periods the production system needs the higher accuracy, called Accuracy-as-a-Service (AaaS), benefiting setup efficiency, costs and flexibility. To validate the presented concept, the proposed model is used for an analog pressure sensor in a fluidic test setup. The control unit of the system is provided with a standard model as well as a more accurate one. It is demonstrated in the paper how the usage of the individual model can improve the accuracy of a special sensor significantly by a factor of four.

Keywords: Sensor Accuracy, Digital Twins, intelligent Digital Twins, Accuracy-as-a-Service

1. Introduction

The increasing need for customized products and greater flexibility poses ever-greater challenges to the producing sector [1, 2]. Facing such challenges, new concepts of digitalization, often called Industry 4.0 in Germany, are arising enabling higher levels of productivity [3]. To realize such flexible production systems, sensors are key elements by providing information about the system enabling higher quality as well as a more efficient production [4, 5]. One key performance indicator for sensors is their accuracy. In order to respond to the flexible requirements posed to production systems, the needed accuracy of sensors can only be realized with high costs originating from the proportionality of accuracy and cost for most of the commonly used sensors [6, 7]. This is fundamentally opposed to achieving increased productivity using low-cost sensors [8]. A possible solution to this challenge of costs versus data acquisition in general and more specific accurate data acquisition will be presented in this contribution. The focus will be on product-related services, which will become a key factor in the future success of a company within the framework of digital business models [9, 10]. Thus, we use instance-specific data in an intelligent Digital Twin, enabling flexible accuracy while focusing on resistance-based sensors.

The further parts of this section provide information about resistance-based sensors, their typical usage and an explanation

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of the Digital Twin. Based on this, section two presents an approach enabling Accuracy-as-a-Service based on intelligent Digital Twins. This concept is then validated on a test setup in section three. The paper closes with a summary and an outlook.

1.1. Resistance-based sensors

Sensors are technical components recording time-variable physical or electrochemical variables from processes and convert them into a unique electrical signal [11]. As displayed in Figure 1, depending on their operating principle there are two types of sensors: Active and passive ones. The passive sensors can be divided into further categories depending on their underlying effect. Three commonly used effects are resistance, inductivity and capacity. With resistance-based sensors being a widely used sensor type in the industry, this contribution will focus on the named category.

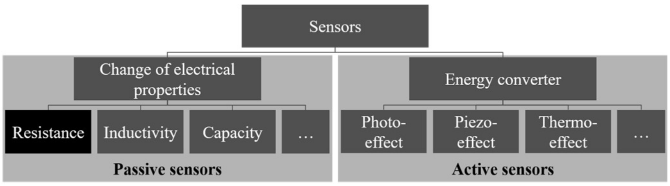

Figure 1: Category of sensor principles [11]

One of the key performance indicators of sensors is their accuracy which can be defined as *“a qualitative performance characteristic, expressing the closeness of agreement between a measurement result and the value of the measured”* [12, 13]. Its opposite is called the inaccuracy of a sensor and describes the deviation between the actual and measured value. This inaccuracy often leads back to production tolerances of the sensing element used in the sensor or its periphery. The two types adding up to the total inaccuracy of a sensor besides fatal errors are [14–16]:

- Systematic errors,
- Random errors.

Besides the two named types, there are also fatal errors which arise, for example, due to avoidable carelessness during a measurement [15]. Random errors have a statistical distribution. Thus, they can only be reduced by repeating the experiment several times. In contrast, systematic errors can be compensated to a certain extent depending on the source of the error. The most important sources of inaccuracy based on systematic errors for resistance-based sensors are [11, 17]:

- Non-linearity,
- Temperature errors,
- Hysteresis,
- Calibration errors of sensitivity and offset.

A typical way to reduce errors is to linearize the characteristic curve [15]. Alternatively, the inaccuracy can be compensated in software, instead of adapting the hardware. For this, however, its influence must be known exactly. One possibility to achieve this is the use of specific data of each sensor instance, the so-called instance-specific data. An example of such instance-specific data is the actual weight of a component or the specific torque speed curve of an electric motor. With the help of these instance-specific data of the individual sensors, a certain part of the inaccuracy of the sensor can be compensated, but only up to a certain degree. One limiting factor is the accuracy of the test bench the instance-specific characteristic is recorded.

1.2. Life cycle and typical usage of resistance-based sensors

Typically, sensors go through multiple companies along the industrial value chain. Starting at a supplier company manufacturing the sensing element, the next step is usually a component manufacturer who applies the sensing element to a specific task through housing and adding peripheral electronics. Afterwards, the generated component is sold to a machine manufacturer or directly to the machine user. Figure 2 shows the typical steps in the life cycle of resistance-based sensors.

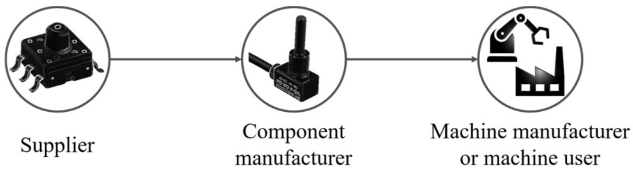

Figure 2: Typical life cycle steps of sensors

Using resistance-based sensors, the typical flow of information passes different stages on its way from the physical process to the control code of the production system, also referred to as measuring chain [14]. A typical structure with an example for each transition highlighted in blue is shown in Figure 3. An example of the measurand is the actual pressure in a tank. At the beginning of the measuring chain, the sensor converts this measurand into a measuring signal [16]. An example can be a voltage between one and five Volt proportional to the pressure in the tank. This analog signal can either be directly converted to a digital signal in the periphery of the sensor or transmitted analog to an input module. The input module either converts an analog input signal to a digital one or directly interprets the already digitized signal to a digital value [16]. One example can be an unsigned integer value between zero and 2^{16}. The control of the production system interprets this digitized value to control the pressure in the tank.

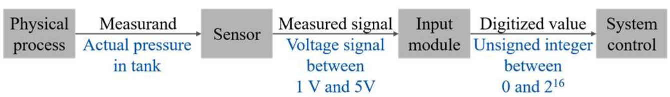

Figure 3: Measuring chain for resistance-based sensors in production systems [16]

To loop back from the digitized value in the control program to the actual measurand, the programmer either manually inserts a characteristic or uses predefined building blocks, mostly supplied by the component manufacturer. This characteristic is often linear describing the complete measuring chain presented in Figure 3. Since the greatest influence on the measurement chain originates from the sensor, this contribution will focus on eliminating its error.

As already mentioned, the requirements for production systems change over time in ever shorter cycles. This also has an impact on the required accuracy of the installed sensors. Currently, there are two possible solutions to cope with these requirements. Either the sensors can be changed frequently, so that the lowest still sufficient accuracy can always be achieved or the production system can be directly equipped with highly accurate sensors. Both options come with higher costs originating from manual effort and the proportionality of accuracy and cost for most of the commonly used sensors.

1.3. Digital Twin

Digital Twin is a concept arising within the context of new technologies coping with the general challenges for the producing industry, often referred to as Industry 4.0 [1, 18]. In literature, a lot of different definitions for Digital Twins exist, due to their novelty and high popularity [2, 19]. In this article, we use a definition in which a Digital Twin is a virtual representation of an object, very often referred to as an asset, enabling it to represent its static and dynamic behavior [20]. It contains all models of the represented object and includes all data from the different phases of the lifecycle, enables the simulation of the physical behavior in the virtual space and is always synchronous with the asset [21]. There are various use cases of Digital Twins such as reconfiguration, predictive maintenance, optimization, and consistency check. All these cases show the benefits of the Digital Twin concept throughout the entire product life cycle from analysis and design to maintenance [21]. The Digital Twin as a general concept can be enhanced through comprehensive models, intelligent algorithms and services leading to an intelligent Digital Twin [22]. Ashtari et al. [22] propose an architecture composed of models, data, and interfaces to achieve the defined core characteristics for Digital Twins. Figure 5 depicts the added value of an intelligent Digital Twin in an automation system enabling different services as real functionalities of real assets.

This service aspect plays an important role in the modern producing industry. Through the fast changing requirements of production systems, good adaptability to changes and new environmental conditions is generally needed. Based on rapidly evolving cloud technologies the service idea is growing. Instead of owning or buying a special system, infrastructure or software, it is just rented or used for the time or task directly needed. From these ideas, the concept of everything as a service evolved to make this approach usable not only for IT infrastructure but also for software. Benefits are predictable costs, increased flexibility, time savings and always using the latest technology. [23, 24]

Conclusion from the introduction: Based on the presented situation, the following conclusions can be drawn for the scope of this article:

- Modern production systems need flexible accuracy at low-costs.
- Accurate sensors are more expensive than less accurate ones.
- Resistance-based sensors are frequently used, which is why we focus on this type of sensor.
- The influence of some causes of inaccuracies can be reduced by knowing their exact specification.
- The concept of Digital Twins is arising and can manage and provide models for individual instances of assets.

2. Concept for Accuracy-as-a-Service using intelligent Digital Twins

The general idea of the concept is to provide an accuracy model to the control of a production system where the corresponding sensor is connected. To overcome the described challenges, the next section presents a new concept to enable Accuracy-as-a-Service based on intelligent Digital Twins. Figure 4 visualizes this idea.

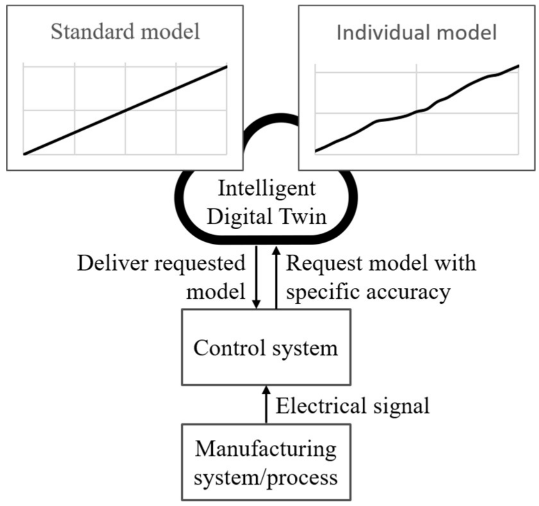

Figure 4: General idea of the concept

The sensor used in a manufacturing system directly interacting with the process generates an electrical signal. This signal is then processed as shown in Figure 3. The last step there describes the conversion of the digitized value to the actual measured value. Up to now, this process was still strongly characterized manually or realized by modules from the manufacturers of sensors, which had to be explicitly obtained for this purpose. With the concept, this interpretation can be realized by the accuracy model working with the standard model as well as with more individualized models. After setting up the manufacturing system, depending on the needed accuracy the control can request a specific accuracy model for a certain period of time. An intelligent Digital Twin can meet this request through delivering the needed model to the control. This process can be executed as often as necessary.

For the intelligent Digital Twin, an existing framework from literature [22] is used. This framework contains the accuracy model and provides the service of delivering the requested models. The framework with its adapted areas is presented in Figure 5. In there the existing parts of the framework such as models, data and interfaces are shown in grey. The extended parts accuracy models and Accuracy-as-a-Service (AaaS) are displayed in blue. The general idea of such a model is to interpret the signal coming from the sensor with the prevailing context conditions and the instance-specific information of the sensor to output the measured value. Examples for prevailing context information are ambient temperature, ambient pressure, air humidity or ambient brightness. Since the sensor to which the concept is applied, is often not able to measure these parameters directly, other sensors that may be available in the system can be used. To access such information the Digital Twin-Digital Twin (DT-DT) interface of the framework shown in Figure 5 is used.

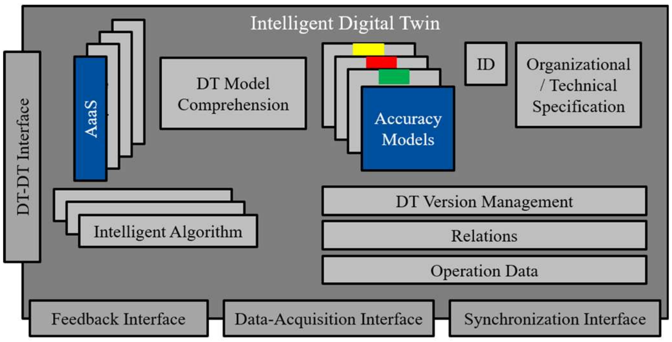

Figure 5: Extended framework of the intelligent Digital Twin [22]

Figure 6 shows an approach for an accuracy model. The input information is used for a case selection taking different application scenarios into account such as the installation direction of a force sensor or the hysteresis of a sensor. After selecting the case to be applied out of the sensor signal or the context information the corresponding multi-dimensional individual characteristic of the sensor is selected. With the help of the sensor signal and the context information, the current sensor value is determined from the appropriate individual characteristic. This represents the output value of the accuracy model.

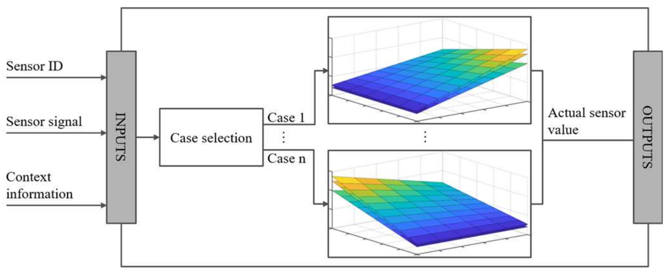

Figure 6: Approach for accuracy model

The pressure sensor from section 4 can be used as an example for such a multi-dimensional characteristic. The actual measurand, which is the current pressure in millibar (mbar), is dependent on the ambient pressure, the ambient temperature and the electrical sensor signal. This results in a four-dimensional characteristic. Based on accuracy models, an intelligent Digital Twin can offer the service of providing control systems with the required models through the AaaS. This can be either a time-dependent service of changing models depending on the needed accuracy or a permanent service when a highly accurate sensor is needed permanently.

The different accuracy models can be provided by the component manufacturer as he often packages and sells the sensors to the users of the sensors as a product-related service. This enables the component manufacturer to build digital business models generating revenue even after the actual hardware has been sold. At the end of the sensor production, the individual characteristics can be recorded on automated test benches. Depending on the desired structure of the accuracy models, the measurement data can then be processed and stored with other development data in an intelligent Digital Twin.

3. Validation

First, an industry-relevant scenario is presented on the basis of which a simplified test setup is derived. The concept enabling AaaS from section two is applied to this test setup and the results obtained follow at the end of this section.

3.1. Application scenario and test setup

A domain where varying use cases require different levels of accuracy is material handling systems using vacuum. These vacuum handling systems are widely used in production systems and automated handling tasks due to their robustness and easy implementation compared to competing technologies [25, 26]. An exemplary vacuum gripping system used in the automotive body shop is shown in Figure 7.

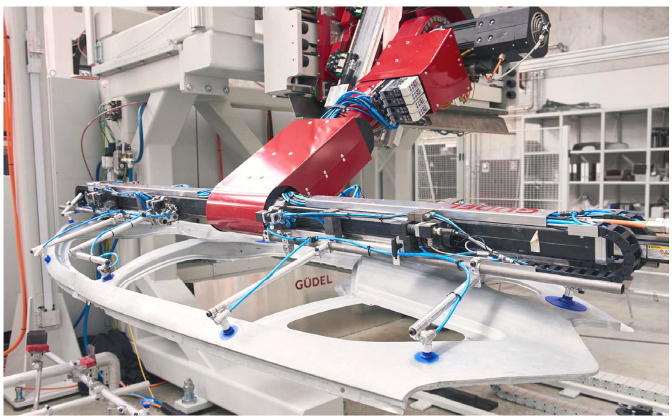

Figure 7: Representative industrial setup of a vacuum handling system [27]

Through their ability to grip the object just from one side, they can easily adapt to different forms, sizes and weights of objects with only little or no modifications [28]. This makes vacuum handling systems an interesting solution for future flexible production systems. Crucial components in such systems are vacuum sensors detecting the actual vacuum level in the system at certain positions. Due to the existing proportionality between accuracy and costs most systems are equipped with low-cost sensors with a relatively low accuracy of ±3% full scale (F.S.) [29]. We use such a low-cost sensor to validate the presented concept. In order to limit the effort, only the relevant fluidic part is assembled as a test setup instead of the vacuum gripping system mentioned above. The test setup consists of a control system, in this case, a Beckhoff programmable logic controller (PLC), the fluidic system, shown in a more detailed way in Figure 8, and the different models that could be provided by an intelligent Digital Twin.

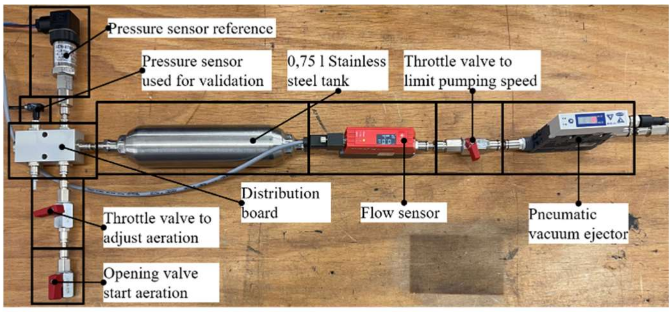

Figure 8: Fluidic part of the test setup

The control system receives the electrical signal from the sensor used in the fluidic system. This voltage signal, in the test setup a voltage between 1 V and 5 V, needs to be converted to a digital value, then interpreted by the control system. The conversion is realized with a 16 bit -10 V to 10 V analog input module. To interpret the digitized analog-to-digital converter (ADC)-value, the models provided by the Digital Twin can be used. Using the standard model, a standard accuracy can be achieved. If a process requires higher accuracy, e.g. defined by the user or the use case, the control system can request a higher accurate model, also available in the Digital Twin. The used standard model was directly generated from the information provided in the sensors data sheet [29]. The individual model, on the other hand, was created on a specific test bench for vacuum components. Both characteristics are presented in Figure 9 while the individual model focuses on the compensation of the offset and sensitivity. However, the offset deviation between the standard and individual characteristics is marginal as shown through the bottom magnification in Figure 9. In contrast, the deviation due to different sensitivity is higher, as shown by the deviation in the upper magnification.

To determine the accuracy of the sensor under consideration for validation of the concept a highly accurate pressure sensor is used as a reference in the test setup presented in Figure 8. The accuracy of the sensor under consideration is captured for increasing and decreasing vacuum levels. However, the pressure changes need to be sufficiently slow to avoid flow dynamic influences. For increasing vacuum levels, this is realized with the throttle valve on the ejector, in case of falling vacuum levels with the throttle valve on the distributor board. In order to monitor the speed of the pressure increase, a flow sensor is used. To further slowdown these processes, a steel tank is installed, which serves as a buffer.

The test sequence begins with the setting of the two throttle valves. As soon as the pressure change is detected slowly enough in pretesting, the actual test can start. To do this, we close the opening valve on the manifold and start the ejector. As soon as an under-pressure of more than 800 mbar,rel is reached, the ejector is stopped and the test for the rising pressure curve is completed. Now we open the valve on the manifold and the pressure drop begins. As soon as the system reaches ambient pressure, the opening valve is closed and the process starts again. We repeat this measuring process ten times while the measurement data is recorded in the PLC with a cycle time of 1 millisecond.

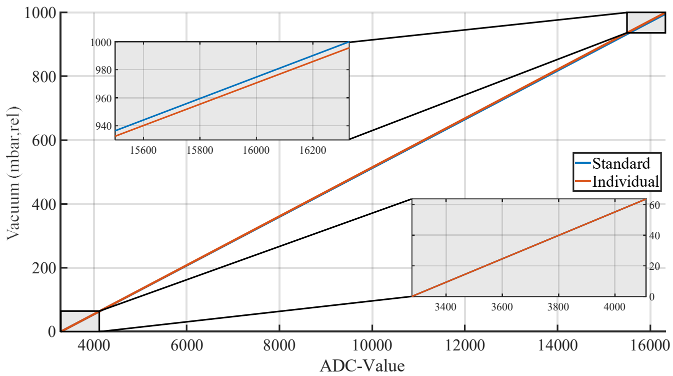

Figure 9: Standard and individual characteristic used in the test setup

3.2. Results

The deviation between the reference pressure sensor and the used pressure sensor is presented in Figure 10 over the vacuum level as a relative value on the x-axis. The red and blue lines show the deviation relative to full scale of the sensor for rising and falling vacuum levels with the standard characteristic. The black and green lines represent the deviation for rising and falling vacuum levels with the individual characteristic.

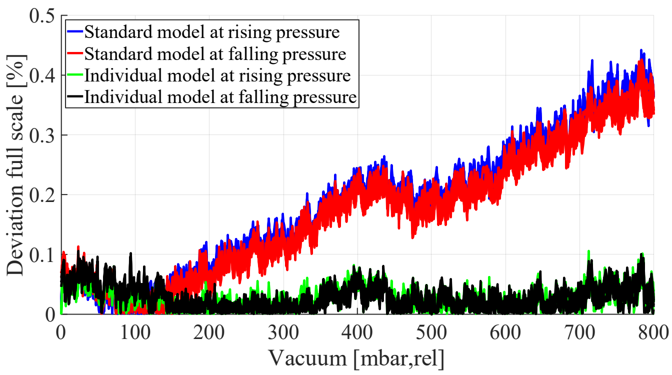

Figure 10: Deviation relative to full scale over the vacuum level

The first observation is that there is no significant variance for neither the standard nor the individual characteristic comparing the rising and falling vacuum levels. This is an indication of low hysteresis. The second observation is the low scatter of the respective measurement configurations in the ten repetitions performed. This indicates a low influence of random errors. The third observation is the significant improvement in accuracy comparing the standard and individual characteristics, even at an already high accuracy level far below 1% F.S. While the deviation with the standard characteristic curve is still slightly above 0.4% F.S., this can be reduced to below 0.1% F.S. with the individual characteristic. This corresponds to an improvement by factor four, particularly for high vacuum levels. Especially in this area, the concept delivers a striking improvement.

4. Conclusion and outlook

This paper presents a concept to enable Accuracy-as-a-Service using an intelligent Digital Twin. Beginning with a classification of resistance-based sensors as industry-relevant, the meaning of the accuracy of sensors in the context of industry 4.0 is presented. However, the current problem is that sensors with higher accuracy are often more expensive than inaccurate ones. One approach to solve this drawback is the compensation of systematic errors in resistance-based sensors with the help of instance-specific data. Based on this, a concept to reduce the influence of some causes of systematic errors with the help of accuracy models provided by an intelligent Digital Twin is presented. To validate this an experimental test setup is illustrated. It shows good improvements of a factor of four for the accuracy of the sensor under consideration using two different accuracy models. These improvements have been achieved despite an already high accuracy of the sensor compared to the accuracy of the reference sensor. With a greater deviation of these two accuracies, an even greater improvement in accuracy can possibly be achieved. This is one of the points at which further research can continue. Besides that, other types of resistance-based sensors could be investigated. Furthermore, the influence of other parts of the measuring chain such as the ADC-Characteristic and their influence on the accuracy of sensors can be looked at too. Since the concept has so far been limited to resistance-based sensors, but sensors used in industry are also based on other effects, the suitability of the concept for other sensor effects can be investigated in future studies.

Acknowledgements

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