



# Challenges and trends in manufacturing measurement technology – the “Industrie 4.0” concept

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**Abstract.** Strategic considerations and publications dealing with the future of industrial production are significantly influenced these days by the concept of “Industrie 4.0”. For this reason the field of measurement technology for industrial production must also tackle this concept when thinking about future trends and challenges in metrology. To this end, the Manufacturing Metrology Roadmap 2020 of the VDI/VDE Society for Measurement and Automatic Control (GMA) was published in 2011 (VDI/VDE-GMA, 2011; Imkamp et al., 2012). The content of this roadmap is reviewed and extended here, covering new developments in the field of the Industrie 4.0 concept and presented with expanded and updated content.

## Translation

This article was first published in German in *tm – Technisches Messen* (Vol. 83, doi:10.1515/teme-2015-0081, Imkamp et al., 2016). It has been slightly revised and expanded (Figs. 5 and 11).

## 1 The “Industrie 4.0” concept

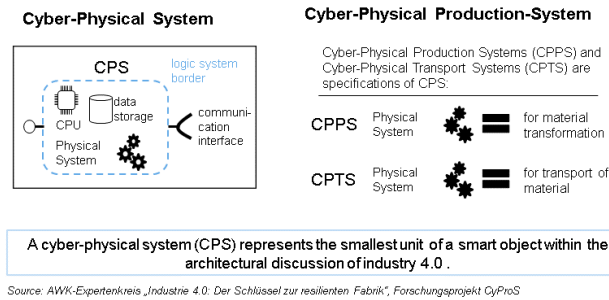
“Industrie 4.0” represents an initiative of the German government for the future development of industrial production (BMBF, 2016). This term is commonly understood as the linking together of the manufacturing industry and information technology as well as all associated activities. The term Industrie 4.0 here stands for a variety of major technical and organizational changes brought about by the increasing

networking of humans and machines. Therefore maximizing collaboration productivity is an important goal.

The primary aim of linking manufacturing industry and information technology is to make production more flexible. This flexibility is necessary as a means of economically countering the demand for customized products as demand fluctuates and batch sizes fall. This demand was also identified as a major trend when the manufacturing metrology roadmap was developed (Imkamp et al., 2012).

Individualized products require a corresponding adjustment of processes, which means that production facilities are frequently reconfigured and associated changes in production control operations are necessary. These changes must be implemented efficiently if companies are to be able to survive permanently in the market.

The basis for this is capturing the current system state and adapting it (automatically, if at all possible) to a new plan



**Figure 1.** Definition: the cyber-physical system (Schmitt et al., 2014).

which takes the changed requirements into account. This corresponds to the image of the real world and its link to a virtual planning model. Measurement technology plays an essential role in capturing the real world.

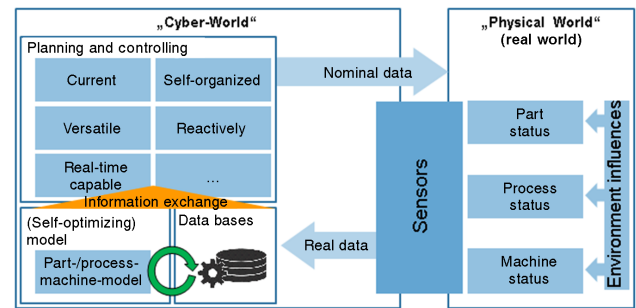
The data collected constitute a central component of cyber-physical production systems (CPPSs) which aim at lifting the current productivity limitations of established manufacturing processes and meeting the requirements of manufacturability and networkability (Schmitt et al., 2014).

## 2 Cyber-physical production systems (CPPSs) and measurement technology

Here cyber-physical production systems (CPPSs) are a special form of the cyber-physical systems (CPSs), which have been increasingly mentioned in the literature over approximately the last five years (Monostori, 2014). A CPS as defined by VDI/VDE technical committees 7.20 and 7.21 is a system which links real (physical) objects and processes to information-processing (virtual) objects and processes via open, partly global information networks which can be connected together at any time (VDI, 2013, 2016) (Fig. 1).

CPPSs are CPSs integrated into production with embedded software which can capture and evaluate data in real time and on this basis selectively intervene in processes. Here, CPPSs take the product, the production and the production system into account and interact with both the physical world and the digital world via multimodal interfaces. The large quantities of data made available thereby not only constitute a great potential of the fourth industrial revolution, but they are also a challenge. With the Industrie 4.0 concept the rational linkage of large amounts of data is a basic condition of generating or improving process knowledge and, building on this, of being able to ensure an optimum control of the processes.

In this context, models are essential for mapping virtually the physical processes and components and also their interaction in the CPS (VDI, 2013, 2016). On the one hand, these models must describe the real processes and components so accurately that they supply a suitable image of the functions



**Figure 2.** Concept of a cyber-physical production system.

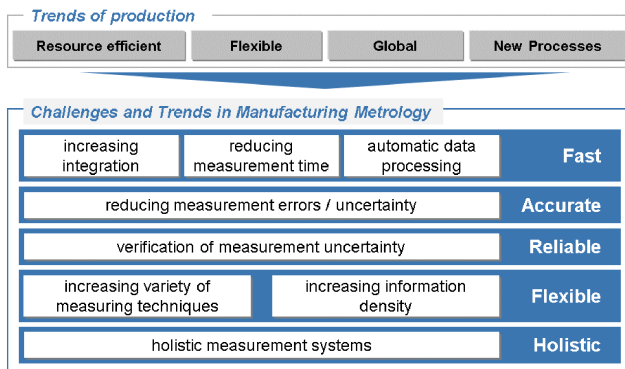
of the system for its planning and control. On the other hand, the complexity must be limited to allow the model not only to be created at reasonable cost but also to be managed by the information technology.

Sensors, which often have a measuring function, are used for linking the virtual and real worlds (Fig. 2). The actual status is transferred into the “cyber-world” as real data in order to derive process information, collect it in databases and use it as a basis for the models which can be adapted (ideally by self-optimization) to the real situations. This concept forms the basis to describe even complex interactions and thus prevent process deviations or enable a response with real-time capability. The appropriate sensor systems thus supply the required information from the real world in order to plan and control the process in the virtual world with the aid of the model (Fig. 2). The integration of sensor and measurement technology is thus a key element in the success of CPPS, even for complex production processes. A central challenge here is collecting the “right” measurement data at the “right” place and at the “right” time. However, even how the collected data are handled has a decisive influence on the quality of the information obtained. A correct interpretation of the measured data becomes more and more important in networked and maximally automated production. The system must also be able to react robustly to redundant and conflicting data. This robustness is also part of the requirements made for resilient production or the resilient factory, which is being intensively discussed in the context of the Industrie 4.0 concept (Schmitt et al., 2014).

## 3 The manufacturing metrology roadmap

In 2011, a German group of experts from research and industry prepared a forecast relating to the future development of metrology in industrial production. It was published in the form of a roadmap under the title “Manufacturing Metrology 2020” (VDI/VDE-GMA, 2011; Imkamp et al., 2012).

The roadmap covers the challenges and trends in manufacturing metrology (named also production metrology, Pfeifer and Schmitt, 2010) under four topic areas with the aspects of “fast”, “accurate”, “reliable” and “flexible”. These head-



**Figure 3.** Requirements and trends from the VDI 2020 Manufacturing Metrology Roadmap (updated in 2015).

ings for describing future development were confirmed in a review of the roadmap at the end of 2015. In addition, a fifth heading – “holistic” – was added to highlight the importance of more complex measurement systems which communicate with the virtual world, not only for a holistic capture of product features but also for improving measurement accuracy and reliability as well as flexibility in application (Fig. 3). The suitability of the sensors and measurement systems used for the CPPSs described is here additionally oriented by the attributes mentioned but expanded by the addition of the “holistic” aspect.

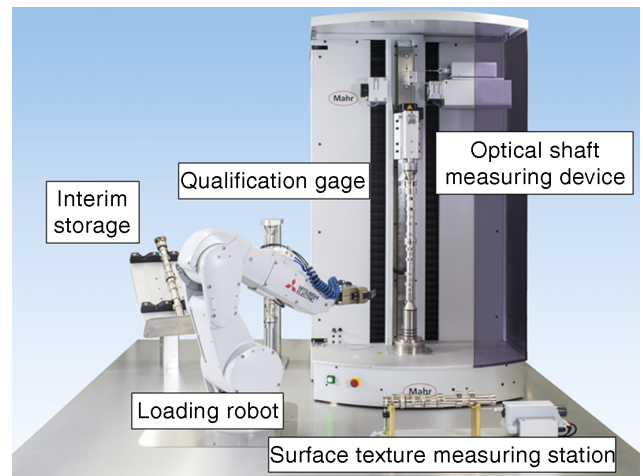
In the context of the Industrie 4.0 concept the importance of measurement technology itself and its digital integration into production becomes increasing significant. In the topics of the roadmap mentioned above – “fast”, “accurate”, “reliable”, “flexible” and “holistic” – nothing is initially altered thereby which concerns metrology as such. Requirements are, however, significantly intensified by the importance of metrology in the implementation of Industrie 4.0, since an increased use of measurement and sensor technology in production is to be expected. Even now, this trend is represented by the enormous growth of this sector in recent years and in its high level of investment confidence (AMA, 2016).

In the following sections, the individual topics are presented starting from the results of the original roadmap.

### 3.1 Fast

Speed plays an important role in production. This is especially true for measurement technology, which in production largely delivers information for conformity checking and process control (Pfeifer and Schmitt, 2010). This information should be provided quickly so as not to slow down production progress.

The rapid provision of information is, on the one hand, achievable by faster measurement processes, as was shown in the roadmap in various examples (VDI/VDE-GMA, 2011; Imkamp et al., 2012). Another example is optical shaft measurement. The sensor of an optical shaft measuring device



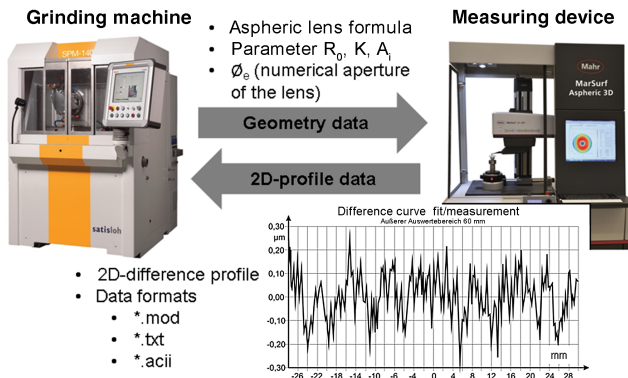
**Figure 4.** Installation for the fully automatic inspection of camshafts by an optical shaft measuring device for diameter and cam position, together with an additional surface texture measuring station.

works on the shadow image principle. By means of a telecentric precision lens and a digital camera, the image of a rotationally symmetrical workpiece is recorded quickly and contactlessly. Figure 4 shows the fully automatic loading and measurement of camshafts in an optical shaft measuring device.

On the other hand, the integration of measurement technology into production processes, particularly by means of automation, can contribute to acquire measurement results more quickly. An automated integration of measurement technology has already been the state of the art for some years now in a number of areas of application, such as compensation for tool wear in grinding (Steffen, 1995), setting EDM tools (Hahn, 2014), and measured-data feedback in the manufacture of bevel gears (“closed loop”, Benetschik, 1996).

A current example from the manufacture of aspherical lenses is the connection of the grinding or polishing machine to the measuring device via information technology (Fig. 5).

The basis for implementation of reliable production process control is formed by information technology links between the measurement systems on the one hand and the production systems on the other. Information about deviations and the correction values derived from these are transmitted for the production processes via these links. The increasing simplification and standardization of the technologies underlying these information technology links (such as linking via computer networks) has brought about further developments in the integration of measurement technology and expansion into different areas of application. This integration goes beyond measurement technology as such and will therefore be dealt with in Sect. 4, which follows the treatment of the individual topics.



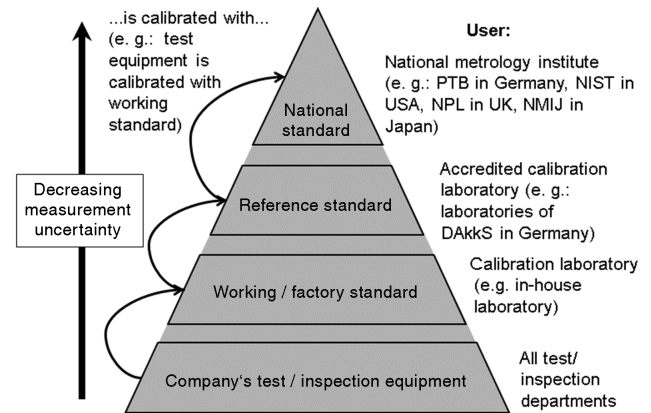
**Figure 5.** Data exchange between manufacturing machine and measuring device for the implementation of a “closed loop” in lens production.

### 3.2 Accurate

The demands for improvements in the quality of products are directly related to reducing the tolerances of quality attributes and parameters and, thus, to a greater accuracy in production and the associated measurement technology. This development has been clearly recognizable in the continuous increase in the accuracy of machine tools and measurement technology over the last 150 years since the beginning of the industrial revolution (Weck and Brecher, 2005). In the field of dimensional measurement in semiconductor production, levels of accuracy on the atomic scale have been achieved meanwhile (Taniguchi, 1983; Beckstette, 2002).

Improvements in the accuracy of primary measuring technology (sensors, transducers) and their calibration continue to play a major part in the further development, as it was demonstrated by a number of different examples in the roadmap (VDI/VDE-GMA, 2011; Imkamp et al., 2012). The improvement in accuracy resulting from a significant reduction in calibration uncertainty plays a central role in the roadmaps of EURAMET, the European Association of National Metrology Institutes (available at: <http://www.euramet.org/>).

As illustrated by the so-called calibration pyramid (Fig. 6), measurement uncertainty increases from the tip of the pyramid (level of the definition of the (base) units) to its base (measurement of products) every time a measurement is passed on. In many areas of modern production, however, the measurement uncertainty is often no longer adequate for checking the tolerances required by the standard. In the field of high-precision gears, tolerances of less than  $1 \mu\text{m}$  are, for example, required by the ISO 1328-1 cylindrical gears standard – an order of magnitude of the measurement uncertainties which can currently be achieved by a metrology institute only. Improvements in accuracy thus can be ensured, on the one hand, by specific actions in the production environment, such as the use of more accurate measuring devices, improvements in environmental conditions or better measurement of



**Figure 6.** Calibration pyramid of the measurement traceability hierarchy (PTB – Physikalisch Technische Bundesanstalt, Germany’s national institute; NIST – National Institute for Standards and Technology; NPL – National Physical Laboratory; NMIJ – National Metrology Institute of Japan; DAkkS – Deutsche Akkreditierungsstelle, Germany’s accreditation body).

these for corrective purposes, and so on. On the other hand, accuracy can be improved by the metrology institutes by developing new standards or even (what is usually more expensive) by developing new and better performing measurement methods, and – consequently – by calibrating the corresponding transfer standards with lower measurement uncertainties.

For measurement technology, meeting the increasing accuracy requirements of the Industrie 4.0 concept is a great challenge for the future. Online acquisition and processing of current and mostly pre-processed measurement data along with associated measurement uncertainties, including their correction or improvements obtained by information fusion of cooperating measurement systems or other sources and connected control loops, are stepping into the foreground. The aim is the creation of the “intelligent measurement process/system” which, before the operational sequence, for example, checks online the evaluation software (EMRP, 2016), the geometrical deviations of the measuring device (see <http://www.ptb.de/cms/de/ptb/fachabteilungen/abt5/fb-53/forschungsvorhaben-53/brechzahlkompensierte-online-korrektur-von-koordinatenmessgeraeten-mnpq.html>) or the environmental conditions, and thus reduces to a minimum the various contributions to measurement uncertainty. Furthermore, it might be expected that future networked digital measurement systems will be capable of performing self-validations and even self-calibrations.

As has already been described under CPPS, measuring devices and above all more complex digital measurement systems will communicate directly with the cyber-world in future. In this way newly distributed measurement systems with a significantly higher content of relevant and redundant information can form flexibly, and thus in principle have a reduced measurement uncertainty for selected manufactur-



ing measurands. Contributing to this are the so-called cooperating sensors and measuring systems with which, for example, different measurement ranges of the same measured quantity can be captured and fused (Ruser and Puente-Leon, 2007). The topic of the Industrie 4.0 concept here offers a source for increasing accuracy by measurement technology. But this development has not yet been considered in measurement theory nor taken up in practice. The corresponding conditions are, however, that the measurement systems and devices which are responsible for measurement uncertainty overwhelmingly are model-based – in other words, even include redundant external measurement information – and able for their part to communicate with the connected components. Here, increasing importance is attached to taking correlations into consideration, including their desirable quotation in calibration certificates (Sommer and Siebert, 2006) and their modeling in multi-sensor measurement systems since these correlations have a significant influence on measurement uncertainty achievable; that is, they can even increase it (Sommer and Siebert, 2006).

### 3.3 Reliable

In manufacturing metrology as in metrology in general, the accuracy of measurement results is described quantitatively by specifying a measurement uncertainty. Put positively, this parameter reflects the certainty and reliability of a measurement result. Measurement uncertainty plays a major role in conformity assessment – the judgment as to whether a measurement result, including measurement uncertainty, does not exceed or fall below the specification limits given. It is obvious that the uncertainty must be considerably lower than the tolerance if making a useful statement about conformity based on the measurement result. This is especially true as it regards decision rules (DIN, 2013) which stipulate that the tolerance must be reduced by the measurement uncertainty. In most cases production planning cannot accept a high proportion of its allotted tolerance being taken up by metrology.

In the present section, we are not concerned with the reduction of measurement uncertainty, something which has already been discussed in the “Accurate” section, but rather with methods of determining it and in the context of the Industrie 4.0 concept of passing it on. It is precisely with safety-critical products, such as medical products (Roithmeier and Wieler, 2011), that these methods are becoming more and more critical since a conformity assessment is no longer accepted unless measurement uncertainty has been taken into consideration. The growing importance of verification is also clearly revealed by the fact that in the new 2015 revision of ISO 9001 (DIN, 2015) the topic traceability of measuring instruments, which constitutes the basis of a measurement uncertainty determination, has been upvalued by having a sub-section devoted to it.

The basis of all investigative procedures is the GUM (guide to the expression of uncertainty in measurement)

(JCGM, 2008), the application of which has been able so far to prevail only in the field of calibration standard and reference measuring instruments. A revision of the GUM is planned (BIPM, 2015). Simplified procedures (Dietrich and Schulze, 2014) with very different levels of detail are often used in production, which may lead to different results in the practical application of these methods. However it remains a fact that the more accurately measurement uncertainty is determined, the better its information that can be used, for example, in automated production control loops. This can include not only re-machining when a tolerance is not proved but also pairing matching components on the basis of inspected geometrical properties.

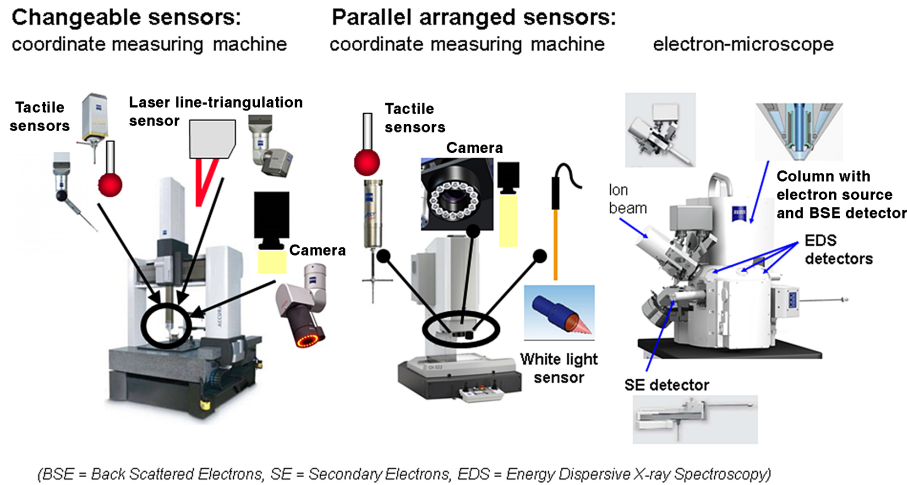
In the roadmap (Imkamp et al., 2012), reference was made to testing methods using virtual replicate measurements based on Monte Carlo simulations of the measurement process. Since this is a testing method which runs automatically, it is predestined for application under the concept of Industrie 4.0.

In future, the use of calibration standards for monitoring measuring processes and the electronic transfer of the relevant data consequently will require digital calibration certificates. Like normal (written) calibration certificates as well, they are used for transferring the results of calibration (best estimates of a calibration result with unit including the associated measurement uncertainty with unit) and also all relevant additional information pertaining to calibration. Due to the increasing proportion of software in measurement systems, the subject of software reliability in the context of the reliability of measurement results is becoming more and more important. One aspect of this is the checking of the mathematical algorithms and the underlying models used in the software utilized. In the determination of surface or geometrical parameters, for example, this could have a major influence on the result. In the meantime, solutions for validating evaluation software have become available on the internet (EMRP, 2016; Bui and Vorbuerger, 2007; PTB, [http://www.ptb.de/de/org/5/53/533/thread/ThreadEA10\\_10.htm](http://www.ptb.de/de/org/5/53/533/thread/ThreadEA10_10.htm)).

### 3.4 Flexible

The variety of measurement systems used in production continues to grow and, thus, also their ability to adapt to different measuring tasks under different conditions, even though the underlying measurement principles are – in most cases – not new. Particularly conspicuous here are measurement systems, such as computed tomography and imaging optical systems, which are able to capture very different features of a component and, thus, respond flexibly to changes in measurement requirements.

Measurement technology is even becoming more flexible by combining measurement systems. In the narrower sense, this may mean, for example, the combination of different sensors on a single coordinate measuring machine. Combining different sensors in a system is, however, common in mi-



**Figure 7.** Examples of multi-sensor implementations in coordinate measuring machines and electron microscopes (BSE – back-scattered electrons, SE – secondary electrons, EDS – energy-dispersive X-ray spectroscopy).

croscopy, especially in electron microscopes (Fig. 7). The term “multi-sensor measurement system” has become generally accepted for this.

In the broader sense, different measurement systems are working together. One example of this flexible linkage of measurement data is correlative microscopy (Elli et al., 2012). Correlative microscopy is the linking together of different microscopy technologies, on both the hardware and the image levels. In this case, the different capabilities of the technologies are combined, for example, with respect to their resolving power. A point of interest found with the light microscope can be quickly retrieved with the electron microscope by using a referenced sample holder for both microscopes. In addition, the image information from the light and electron microscopes can be overlaid by the reference on the sample holder.

Different sensors are used depending on the terms of reference and nature of the product to be tested. This is not simply a matter of equipping a device with multiple sensors but rather of making an appropriate selection or combination of the results from different kinds of sensors. This is referred to as data or sensor fusion (Weckenman et al., 2009). It is also a first step in the direction of virtualizing the sensor system. By linking sensors to a process model and combining correlating measurement quantities, virtualization here opens up new possibilities in the measurement of process variables.

The flexibility of measurement systems is supported by the increasing modularization of the sensor system. In addition to the actual physical sensing element, sensors often now have additional components which allow them to act as an interface in a CPPS in the sense described above. The integration of additional functionalities in the measuring sensor creates a “smart sensor”. Here, this intelligent sensor type should be rendered capable of combining data acquisition

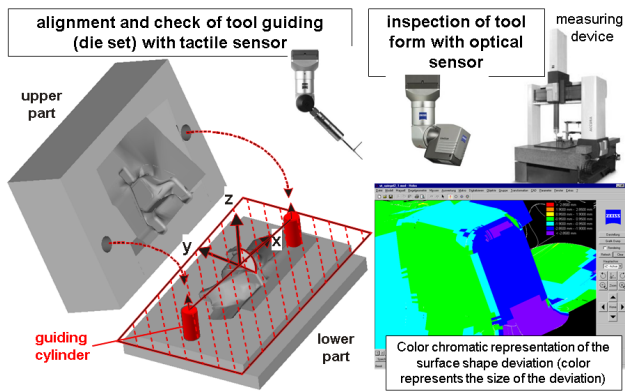
and data processing. Here too, flexibility means adaptation to changes in measurement tasks.

### 3.5 Holistic

In this context, the holistic evaluation of products means that the relevant quality characteristics are brought together to form a complete basis for evaluating product quality. Consequently, the aim of applications of measurement technology is no longer to acquire and process individual measurement values and product characteristics separately.

As with virtual sensors, the essential basis for such procedures lies in the availability of models for the product, for production and for the mechanisms of action prevailing there, as well as for the measurement process. The models have the job of putting the measurement results obtained into a context shared with the relevant product characteristics. Models of this kind can describe the geometry of the product (as CAD models, for example) but also include functionally relevant product characteristics or describe the behavior of the product under measurement (for example, models for geometric measurements on non-rigid sheet-metal components or the measurement of components under thermal loading). The models form, as it were, the link between the product and its characteristics on the one hand and the measurement results on the other, and thus enable measurement results to be interpreted in terms of product quality (Schmitt et al., 2014).

This merging of all information contributions – measuring results from different measuring systems, the inclusion of additional information sources such as geometrical models, material laws or characteristics of the measurement process – can be described as information fusion by extending the concept of sensor fusion introduced above. This is carried out on the technical level by a computerized link between the systems involved and is the basis of the “cyber” aspect of CPPS.



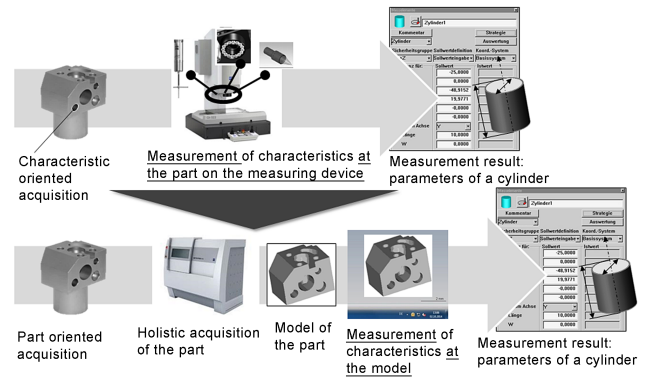
**Figure 8.** Application example of combined sensors use for holistic inspection of a forming tool on a coordinate measuring machine (Imkamp, 2015).

The “Flexible” section of the roadmap already listed several measurement systems for the flexible acquisition of product characteristics (VDI/VDE-GMA, 2011; Imkamp et al., 2012). Measurement systems of this kind are created not only by combining different measurement procedures in a single device but also by means of separate, predominantly optical methods. By a combined application of the measurement procedures these measurement systems implement a more holistic acquisition of the product than would be possible with separate sensors.

A typical example of a measurement method which can describe products holistically is computed tomography, which, on the basis of its measuring principle alone, can acquire not only the entire external geometry but also internal structures and even materials on the basis of their density (Kruth et al., 2011).

Another example is the guidance and alignment elements of a multi-part tool with their extremely reflective functional areas which are captured by a tactile sensor in order to determine the position of the tool in space. As regards this alignment, with the aid of a geometric model (CAD model) the shaping functional surfaces of the cavity are measured with a high point density by an optical triangulation sensor in a much shorter time than with a tactile sensor. This ensures not only that the functional surfaces comply with tolerances in their shape but also that they are positioned correctly within the cavity so that the various tool components which are mutually positioned by the guidance and alignment elements fit each other correctly (Fig. 8) (Imkamp, 2015).

Another example is optical measuring systems which are used in material testing to capture holistically the deformation of the products under stress (Frenz and Schenuit, 2009). Here, a deformation model describes how the product must respond to mechanical stress in order to meet quality requirements. Measurement is then used to check the extent to which the product corresponds to the model.

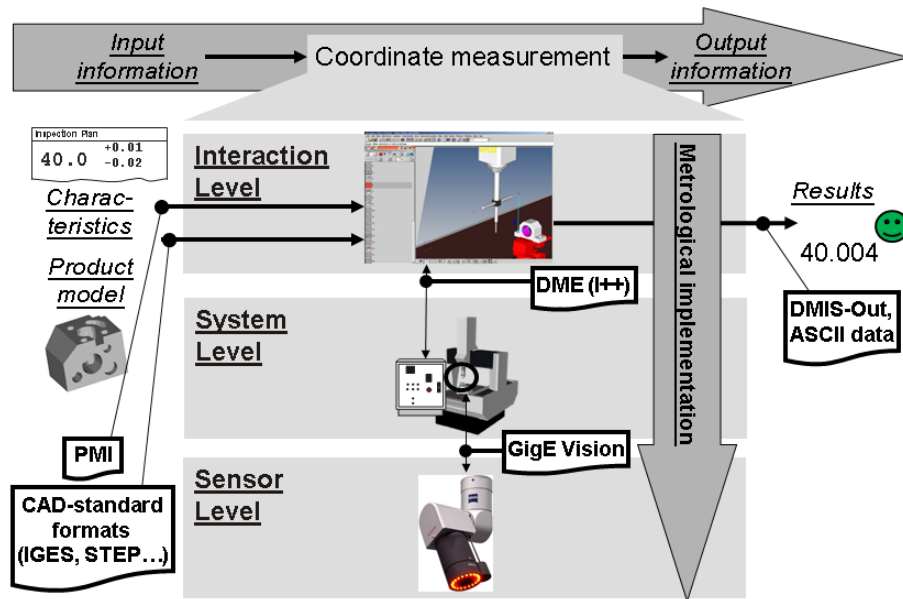


**Figure 9.** Procedure for characteristic (top) and part-oriented (below) acquisition of product shape.

In measurement technology, holistic methods have produced new business models since they make it possible to separate the creation of a product model on the one hand and the measurement process on the other. In the holistic methods for capturing the product shape, not each measurement characteristic and the associated surface data are measured, as it is usually the case, by means of coordinate measuring machines with sensors mounted on them but rather the entire product is captured and a computerized model created. The characteristics are then measured at the model itself (Fig. 9). There are service providers who use their measurement systems solely to produce a product model of this kind and supply it to their customer. The customer then refers to the model to select the characteristics important for him.

In research, the holistic approach is seen as the basis for anchoring the CPPS concept in modern production. Measurement technology – expanded by taking the entire measurement process into consideration and consequently the production process as well – represents here the only possibility of avoiding the productivity trap. “Productivity trap” means the restriction of modern production systems by the system-inherent properties of cycle-based and assembly-line production. This concerns, in particular, the following: unused skills or low adaptability of machinery, unused times in clock-pulse controlled systems, and shutdown and repair times induced by uncontrolled disturbances (Schmitt and Große-Böckmann, 2014).

The presented expanded approach to obtaining and evaluating measurement results makes clear the growing importance of holistic acquisition and shows why the “holistic” aspect is becoming increasingly relevant to metrology – and vice versa.



**Figure 10.** Levels of information technology connections (interfaces) in a coordinate measuring machine with camera sensor (PMI – product and manufacturing information, DME I++ – dimensional measurement equipment interface).

#### 4 Measurement technology in the information technology environment: communication and standardization

The trend towards integrating measurement technology into production has been described in the manufacturing metrology roadmap. Here, the increase in speed arising from integration stood in the foreground. It continues to be of great importance since many measurement processes are slower than production processes (injection-molding, for example) (VDI/VDE-GMA, 2011). In addition to speed, there are other reasons for advancing further with automating the information technology integration of measurement technology. One reason in particular concerns adaptation to individual tasks, which in the broader sense could be referred to as greater flexibility.

However in the final analysis these reasons do not play a decisive role in the technical implementation of an information technology integration of measurement technology into production. It is rather the interfaces and their standardization which are of critical importance. This means not only mechanical and electrical interfaces but also information technology interfaces.

Interfaces are used on different levels within measurement technology and for linking the measurement technology with its environment. Figure 10 shows these levels by means of the example of a coordinate measuring machine with a camera sensor. At the sensor level, interfaces serve to integrate various sensors into the measurement system (such as a camera via GigE Vision, <http://www.visiononline.org/vision-standards.cfm>), which communicates with the higher

interaction level via a software interface (Imkamp et al., 2006). On the interaction level, the measurement system software communicates with the user. In addition, there are also informational links not only to input information in the form of data about inspection characteristics (such as PMI: Product Manufacturing Information with metrological information, Imkamp and Gabbia, 2014) and about product shape (for example, CAD data in different standard formats, such as IGES or STEP) but also links to output information in the form of measurement results (for example, the standardized DMIS-Out format or other ASCII-based formats, Pfeifer and Imkamp, 2004).

At the level of a sensor, mechanical, electrical and also information technology interfaces play an essential role. The interfaces differ significantly with regard to the different measurement technologies employed and can, therefore, be standardized only to a limited extent. There is, however, a clear trend towards using standard interfaces from the network field and from the consumer sector, which can be seen, for example, in the developments of interfaces for cameras used for metrological purposes. In the early period, special plug-in cards, so-called “frame grabbers”, dominated. Today, these have mostly been replaced by high-performance Ethernet-based interfaces and USB interfaces (Farber, 2014). Software products mounted on these interfaces are available for communicating with the camera but are scarcely standardized.

Looking at the interaction level of a measurement system, the system can usually be accessed via a networked computer, with aspects of mechanical and electrical integration being handled via standard interfaces. The information tech-



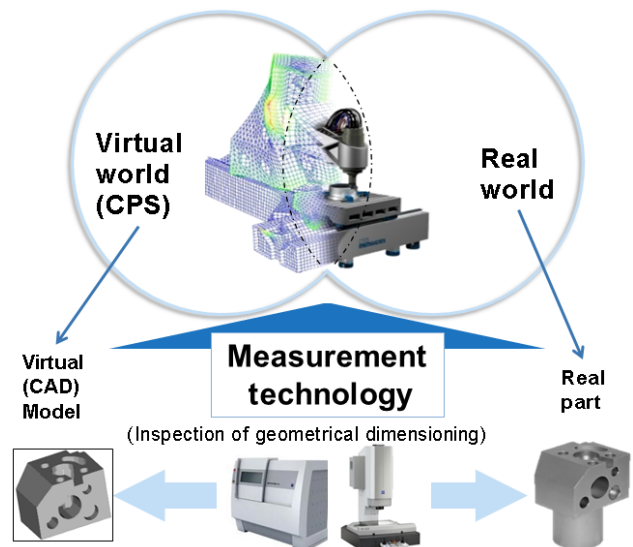
nology interfaces play a role only at this level and are often independent of the measuring technologies used. Information about measuring tasks (such as nominal data, tolerances) and measurement results (such as actual values) is exchanged here. Despite the independence of electrical and mechanical aspects and the thus apparent simplicity of the interfaces, standardization has only succeeded within narrow limits (Imkamp and Gabbia, 2014). The same is true of interfaces for integrating measurement systems into automatic production lines (Imkamp and Frankenfeld, 2009).

In addition to the links shown in Fig. 10, another aspect of the information technology integration of measurement systems is an access to measuring devices via the internet for condition monitoring and preventive maintenance planning (Grieser and Imkamp, 2004). Online support for the user is even possible via this kind of access. The internet’s conventional technologies are predominantly deployed here. A condition of this is access to the corresponding communication interfaces in the measurement system user’s network although this does not always function smoothly because of safety concerns.

A fundamental requirement in the control, regulation and assessment of manufacturing processes is the communication between sensor and actuator or between measuring device and processing machine. What all of these processes have in common is the exchange and interpretation of measurement results and passing them on coherently and reliably. In the first place, as has already been stated, technical approaches are necessary which enable functioning communication and networking in the metrological field; secondly the basis of this communication must also be normatively anchored. The provisions of metrology, which have been recognized internationally for decades, should be selectively adopted to the concept of Industrie 4.0 for the communication channels which relate to measurement values. The cost-effective, readily interpretable and safe passing on of measurement results should here be conveyed by SI units. In the interest of the European economic area and the worldwide networking of production, imperial units such as the inch, degrees Fahrenheit, pound, horsepower and others should be avoided. In addition, three components are essential to a complete specification of a measurement result: the best estimate of the measured value, the unit and the associated measurement uncertainty (EMPIR, 2016).

## 5 Summary: “Measurement Technology 4.0”

It remains to be seen whether the increase in expansion in networking of information and measurement technology justifies the use of the term “Measurement Technology 4.0”. Measurement technology has always made heavy use of components from information technology. A large number of technologies and methods in, for example, coordinate metrology or computed tomography would not be possible



**Figure 11.** Measurement technology for linking the virtual and real worlds, with an example from coordinate metrology for comparing the nominal (CAD model) and actual product shape.

without advanced information technology. Alongside the concept of networking, the handling and further use of data is an aspect with which research and development in manufacturing measurement technology have been concerned since the 1980s. Here, in areas of interest such as the feedback of data into the manufacturing process, concepts and technologies have come into being which can already help answer questions about the concept of Industrie 4.0. Therefore, measurement technology in production should not see itself merely as a supplier of data for the important interfaces of the Industrie 4.0 concept. Measurement technology and the information thereby gained is rather the pacemaker in the concept of Industrie 4.0, and this is made clear in particular by its role in the cyber-physical production system of linking together the “cyber-world” and the “real world” (Fig. 11). Processes in the cyber-world can only be virtualized on the basis of validated measurement data. The validity and processing of the data is – and will remain – a central object of research in manufacturing metrology – especially in the age of the Industrie 4.0 concept. Metrology must therefore play a forerunner role in the development of the concept of Industrie 4.0.

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