Metrology for the digital transformation of the economy and society

We are in the middle of a digital revolution. And this revolution is disruptive: Much of what was normal and sensible yesterday is outdated today and must become faster, more flexible and more transparent. In households, trade and industry, new opportunities are being created everywhere by digital data traffic. The "Internet of Things" (IoT) is driving this development at breakneck speed: machines exchange information directly with each other via digital interfaces. Entire production processes are already fully networked or have digital twins in a cloud. The catchphrase is "Industry 4.0". Measuring devices are also in part inseparably linked with digital technology and automated data processing. This creates enormous amounts of data, the evaluation of which opens up new possibilities for communication and new fields of business. The increasingly rapid development of methods of artificial intelligence (AI) acts like a catalyst for this and is accelerating digital transformation even further.

This transformation is a major challenge to the sophisticated system of quality infrastructure (QI), consisting of metrology, accreditation, conformity assessment, norms & standards and market surveillance. As the national metrology institute of Germany, the Physikalisch-Technische Bundesanstalt (PTB) plays a key role in preparing QI for a digitalized world. To achieve this, PTB has compiled all the necessary tools under the umbrella of a comprehensive digital transformation strategy – from digital calibration certificates and virtual measuring instruments to research data management and to digitally supported testing and approval processes which include data handling without media disruption. These form the basis of the work on complex networked systems and on artificial intelligence methods which has already begun.

Meanwhile, digital transformation projects cover all areas of PTB – from administration to research and to daily interaction. This also includes current developments toward a digital customer portal and e-files as well as metrology for AI, research data management and digital certificates and processes in quality infrastructure. This makes the networking and interlinking of these developments that much more important. The Steering Group for Digitalization (LK-D) and the "Coordination Digitalization" Working Group in the Presidential Staff of PTB are precisely securing these things.

This study outlines some of the current progress and provides an outlook on future developments. The current pandemic situation is one of the main reasons why the digital transformation of work and communication processes has come into sharper focus. At the same time, numerous new projects have been launched in research, for example. In particular, the upgrading of quality infrastructure for digital innovations and the innovative use of digital technologies in quality infrastructure are the focus for PTB – i.e. the development of an interoperable "QI-Digital" system that is prepared for a digitalized world.

Digital Transformation: Core Objectives of PTB

Digital transformation is an ongoing process with ever-shifting focus points. PTB has therefore chosen five core objectives for its digitalization activities. These serve as orientation and guard-rails in the development of new projects and ideas. At the same time, they serve as anchor points for the communication of long-term goals and concepts of metrology for the digital transformation of the economy and society.

Core Objective 1: Also in a digitalized world will PTB be committed to ensuring uniformity in metrology

The quality infrastructure (QI) in Germany is an essential guarantor of economic success. QI is based on the interaction of metrology, standardization, accreditation, conformity assessment and market surveillance. As the national metrology institute of Germany, PTB plays a major role in this. One of its core legal tasks is to ensure the uniformity of metrology according to the Units and Time Act – especially the dissemination of the measurement units in the sense of metrological traceability. PTB is thus a guarantor for ensuring measurement trueness, measurement stability and testability and strongly supports international harmonization in these areas. In the course of digitalization, numerous new challenges are arising; PTB is actively meeting them.

One example that has a great impact on the economy and society is the digital transformation of the energy transition. Without smart grids, which digitally support the interaction between decentral energy supplies, a successful energy transition will be very difficult to achieve. Reliable measurements of power consumption and grid parameters as well as their communication via digital infrastructures are an important building block in this process. The formally launched roll-out of Smart Meter Gateways (SMGWs) in the beginning of 2020 is an important initial step in this direction. SMGWs combine metrological requirements with security-related requirements and requirements of verification legislation. This underlines the necessity of strong interdisciplinary collaboration and effective coordination.

In order to be able to ensure uniformity in metrology even in a digitalized world, PTB is, for example, developing digital calibration certificates (DCCs), is researching the comparability of real and virtual measurements in the "Metrology for Virtual Measuring Instruments" (VirtMet) Competence Center and is working on objective evaluation methods for machine learning and artificial intelligence (AI). PTB has made great strides in all those areas in the last two years. A stable version of the DCC is available and is now the basis of coordination with international partners from metrology, research and industry. At VirtMet, several cross-departmental projects have been started and initial success has been achieved. For the evaluation of AI methods, numerous projects have been launched and the first procedures have been published, especially for applications in medicine.

Core Objective 2: PTB participates in the sustainable usability of research results and data

Data-driven research and business can only be implemented if reliable data is accessible and sustainably usable. Accordingly, research funding institutions increasingly demand that research results be properly documented, archived for the long term and, if possible, made publicly available. These requirements for data management are summarized by the acronym "FAIR Data": Data

should be findable, accessible, interoperable and reusable. In this way, previously evaluated and published data can then form the basis for new questions and research work. These principles are also increasingly finding their way into industry, where a data infrastructure system is to be set up with GAIA-X. PTB has been actively involved in this from the beginning and is working on the further development of the Metrology Cloud to integrate GAIA-X and "QI-Digital". This is to serve as the basis for a "QI Cloud" which is based on the Metrology Cloud. This QI Cloud connects QI stakeholders, digitalizes regulated processes and thus enables new value creation and the exploitation of synergy effects.

The National Research Data Infrastructure (NFDI) and the European Open Science Cloud (EOSC) are the counterparts in the field of science. In the field of NFDI, PTB participates in the standardization of metadata, data quality and persistent identifiers for data. As a member of the NFDI association, these activities will be significantly expanded. In the field of EOCS, PTB is participating within the framework of its activities in EURAMET (the European metrology organization). Here, PTB coordinates the TC-IM 1449 project with the aim of providing research data of the European cooperation projects in accordance with FAIR principles and of promoting cooperation between EURAMET and the EOSC.

Overall, PTB is pursuing the goal of establishing data-based research and development with assured quality and reproducibility. For this reason, PTB is engaged, among other things, on a comprehensive concept for research data management, the development and implementation of a Software Quality Framework, establishing an electronic laboratory book and the consistent use of metadata and vocabulary in the digital environment. Within the framework of individual consultations, researchers at PTB receive, upon request, information on all tasks connected with research data management: creation of data management plans, documentation of the work steps, storage and publication of data and the selection of file formats and metadata formats.

The International System of Units (SI) – the development of which PTB has actively been involved in for over 100 years – is the backbone of all data in industrial and legal metrology far beyond German and European borders. The SI alone is the mother of all internationally accepted, interoperable and reusable data. In 2019, PTB and its partners from industry and research successfully agreed on a universal metadata model (D-SI) for smart metrological data based on the SI. This is the key to measurement data formats which are to endure in new digital environments such as the Internet of Things (IoT) and cyber-physical systems and must especially be understood by machines as well as humans without error. Digital applications such as those used in healthcare or for domestic meters would be absolutely unimaginable otherwise if the data formats used were not reliable. D-SI is already being widely used in the European flagship projects SmartCom and GEMIMEG-II on machine-readable digital calibration certificates. In addition, PTB's online certification for the application of D-SI is unique throughout the world. D-SI uses the machine-usable TraCIM platform which has already been established for many years in coordinate metrology.

The prospects in the international world of metrology are the continued international coordination of smart metrological data formats by the Metre Convention – the group of 62 member states and 40 associated states known as the CIPM that defines worldwide standards such as the SI. In its leading position in two new committees on the "Digital SI" established in 2019, PTB is actively advancing developments in this field. In October 2020, the CIPM endorsed a joint strategy

of the committees for digital data, services and tools on the basis of the SI and encouraged the national metrology institutes such as PTB to push this development (decision CIPM/109-17). With this international mandate, PTB will continue to align and link parts of its research and development with international harmonization under the CIPM.

Core Objective 3: PTB develops holistic concepts for the handling of measuring instruments and measurement data

New measurement instruments often contain distributed, partially virtualized components and use services from the cloud. However, in regulated areas, the hurdles in terms of approval and conformity assessment are high when measuring devices contain such modern communication and information technologies. Manufacturers increasingly see this as an obstacle to innovation and fear long-term competitive disadvantages. Therefore, in a digitally networked economy and industry, holistic concepts for the handling of measurement data and linking measuring instruments digitally are necessary. This also considers the fact that these concepts must meet the requirements of legal and industrial metrology. Up to now, these two areas have been largely separated in their metrological treatment, as they are subject to different legal and organizational framework conditions. In the course of the digital transformation, however, these strict categories are becoming increasingly blurred as similar components are used and data is partly to be applied across the boundaries of the two areas.

A suitable data model for the communication of measurement data, a connection, for example, to the "Metrology Cloud" as well as the efficient use of digital information about the measuring device should ideally already be considered during the development; in other words: "Metrology by design". With its activities on the D-SI, the Metrology Cloud and digital certificates for calibration and conformity assessment, PTB actively supports the development of this principle. With the establishment of a demonstrator for the integration of digital certificates in digital processes on the basis of the Metrology Cloud, PTB has already begun the actual implementation. PTB is also participating with the VDMA in implementing the D-SI data model in the OPC-UA communication standard for Industry 4.0 applications and with NAMUR in standards in chemistry. The wide range of PTB's subject areas is also reflected in these diverse collaborations in digital transformation.

Core Objective 4: PTB supports the efficient and safe use of digital technologies

PTB develops and uses digital technologies both for its own workflows and for quality infrastructure processes. In doing so, it considers the concepts of "security" and "privacy by design" to be indispensable for securing trust. This means that in the development of hardware and software, data protection is taken into account from the very beginning on the one hand, and on the other hand, attention is paid to reducing weak points and sensitivity to attacks as much as possible. The individual components of this digital transformation are intended to be combined in such a way in the medium term that they result in a uniform overall picture. PTB has remained committed to this core objective in the current pandemic situation. PTB intentionally relied on free open-source software to expand the digital tools for communication and collaboration which can later be seamlessly blended with other tools. The use of new tools is evaluated in a joint process involving users and data privacy, information security and digitalization experts. A steering group has also

been set up for this purpose, a continuous structured evaluation process has been initiated and the establishment of a central unit for software development has been launched.

One of the most important building blocks in PTB's digital toolbox is the electronic file, or "e-file" for short (German: "*E-Akte*"), a central electronic document management system in which all PTB documents are conveniently stored and retrieved and which supports spatially flexible, joint work. In particular, the digital transformation of the processes based on these documents is an important element. Taking the findings of the pilot processes, the roll-out began at full speed in 2020. The different areas of PTB are now successively being incorporated into the e-file system. To ensure efficient and effective use, PTB relies on a comprehensive training and information concept. To be able to continue this process even in a pandemic situation, these concepts have been increasingly virtualized and video instructions have been specifically added.

Another digital building block is the customer portal "e-services" (official German name: "*E-Services*"). With this service, web-based processing of ordering data – which is closely linked to PTB's e-file system – is to be set up. The customer portal will be the central digital contact point for customers from the field of conformity assessment and calibrations and will ensure the easy upload of information and the management of orders. Integrating these building blocks with other digital developments and tools is the aim of the "Digital Workflow for Metrological Services" ("*Digitaler Workflow für metrologische Dienstleistungen*") project described below.

Core Objective 5: PTB promotes the active participation of all employees in the digital transformation

Even before the current pandemic situation began, PTB relied on modern tools and processes to involve all interested parties. During the course of last year, for example, a wiki was added to the pool of centrally provided services as a digital knowledge repository. This has created another central contact point where, for the first time, information can potentially be shared with all employees on an equal footing. The current pandemic situation in particular demands a high degree of flexibility and adaptability. At PTB, too, many employees now frequently switch to working at home whenever tasks allow this. To reduce additional burdens during these times, the means of maintaining contact and interaction have been significantly expanded.

These measures are always carried out with the input of employees and interest representatives in order to take concrete needs and concerns into account. An important aspect of integrating this input took place this year during the "Digital Workplace – Meeting Challenges Together" ("*Digitaler Arbeitsplatz – Herausforderungen gemeinsam meistern*") theme week. The theme week was an online event with new features which were being used this way for the first time at PTB. Various topics were presented via a centrally provided homepage on the intranet. Before the actual event began, all interested parties could inform themselves there and using several other communication channels. During the event, the attendees were able to ask questions and have them answered live using a browser-based collaboration tool. A closing discussion round and a bonus theme week quiz rounded off the package.

In many areas of PTB, software is being developed to handle measurement tasks or research questions. An important building block of PTB's digital transformation is therefore networking and the participation of developers. To this end, PTB is promoting community building by holding

regular meetings. Furthermore, various communication channels are being established and expanded and collaboration tools are being created to support the use of innovative technologies and proven software engineering standards.

The digital transformation of metrological services

PTB provides a wide range of metrological services which build on its research and development work. The digital transformation of internal processes for these services thus extends across all departments and subject areas. At the same time, a coordinated approach and a meaningful harmonization of digital processes are necessary to reap actual benefits from the digital transformation. That is why PTB is pursuing the aim of establishing an intertwined digital workflow for metrological services. The various plans, projects and ideas at PTB are being digitally interlinked for this purpose, thus creating new synergies and at the same time creating new impulses. Continuous digital work processes will create greater efficiency and transparency in the future – not only for all employees of PTB, but above all also for our customers.

The work processes of the services carried out by PTB display quite a similar basic structure and can be roughly divided into the following elements: placement of an order, processing an order, performing examinations, issuing a certificate, drawing up an invoice and providing the certificate.

Figure 1: Workflow for the metrological services of PTB

Thanks to numerous expert groups, the digital transformation of the individual elements is already very advanced at PTB. In the future, these building blocks will be blended into an interoperable, digital overall process for all metrological services through the consistent use of metadata.

The first element in this workflow, the **customer portal "*E-Services*"**, which is currently being set up and is scheduled to enter pilot operation in the middle of 2021, serves as a competent customer support system for all PTB services. In the future, it will be possible for communication between PTB and customers to exchange documents and information to take place entirely via this platform. A personal customer account also serves the purpose of recording and maintaining administrative data. Using a uniform web interface, it will be possible to send all orders directly and easily to PTB and to upload the necessary supporting documents as machine-readable documents. This information, together with all related metadata, will be transferred directly to PTB's

e-file. Via the order list stored in the system, customers can also conveniently view the current processing status at any time or submit a follow-up application without having to resubmit the specific documents. This transparency in PTB's actions is made possible by the direct link to the e-file.

Based on the automatically generated metadata stemming from E-Services, a corresponding step is created for the order in the e-file. Implemented document templates aid the documentation and evaluation of the incoming documents. The necessary processing procedures and routes are clearly defined in the e-file and thus ensure transparent and much more efficient work. In the future, the **metadata** assigned to each order will be used in each new work step and successively expanded so that, for example, it can directly flow into the creation of digital certificates without media disruption.

Before the certificate is issued, classic testing of the equipment, software, etc. must still be performed. To ensure a digital process without media disruption here as well, PTB is currently involved in developing suitable interfaces to the diverse tools which are already in use. In doing so, the flow of the metadata from the e-file to the commissioned testing laboratory must be ensured, as must their subsequent retransmission.

After successful testing, a **digital certificate** which takes the requirements of ISO 17025 into account will be issued by PTB. PTB performs roughly 5000 calibrations of primary measurement standards for industry every year. Calibration is thus PTB's leading service business – in 2019, for example, it had a 44 % share of all services. In order to make this business digitally viable, not only in process handling, PTB is focusing in particular on the development of harmonized digital formats for the transfer of calibration results that can be used not only by humans, but by machines as well. Against this background, new approaches will emerge in the medium term that link data between processes without media disruption and in a way that can be automated – something that was previously impossible or too inefficient with analogue calibration certificates. A **digital calibration certificate (DCC)** has already been under continuous development since 2017. For this purpose, an exchange process is being conducted with PTB's calibration laboratories as well as with representatives from industry, science and metrology. The important associated projects in the process of achieving this are the European-funded SmartCom (2018-2021) research project which – coordinated by PTB – is promoting the harmonization of the DCC in Europe, as well as the GEMIMEG (2019) and GEMIMEG-II (2020-2023) projects which focus on the application of the DCC in the Industry 4.0 environment. With the first international "DCC Conference" in October 2020, PTB laid the foundation for international harmonization and joint further development as well.

In the meantime, the DCC definition has become available in a stable version as an XML data structure and forms the basis of many further projects. Building on the DCC, digital certificates for conformity assessment (D-CoC) are being developed and the first links to the e-file system of PTB and the Metrology Cloud are being defined.

The conformity assessment of instruments in legal metrology represents the second largest part of PTB's service business after calibration. For this purpose, the Digital Certificate of Conformity (D-CoC) is already being actively developed as a counterpart to the DCC in legal metrology. The

first prototype of an XML structure for the digital conformity certificates has been available since the year 2020 and is continuously being developed further.

Against the background of the increased use of e-files, an increasing adaption of digital certificates and the requirements for services according to the Online Access Act (*Onlinezugangsgesetz* – OZG), PTB has also been pursuing the introduction of **electronic signatures and seals** as a high priority since 2020. Based on sample processes, PTB's initial basic concept for electronic signatures and seals is planned to be drawn up by about the middle of 2021. Its core requirements will include the relevant legal and technical framework conditions, among other things the eIDAS Regulation (*eIDAS-Verordnung*), the Trust Service Act (*Vertrauensdienstgesetz* – VDG), the legal opinions of the Federal Network Agency regarding digital signatures, traceability to the Digital Intermediary Archive of the German Federal Government (DZAB), ISO 17025 as well as ISO 17065 and a long-term preservation of the value of evidence. In line with the eIDAS Regulation, PTB will thus apply Europe-wide approved qualified signatures and seals in the future. As soon as the basic concept is ready, the first pilot organizational units of PTB will be able to issue completely digital documents and certificates with the necessary security to partners and customers in industry using the new electronic signatures and seals in the second half of 2021. As a part of this process, PTB is planning to set up a seal office. PTB-wide implementation is planned for 2022.

Last but not least, the comprehensive digitalization of PTB's metrological services also includes the creation of **electronic invoices**. These, of course, are still being drawn up with SAP, but for a media process without disruption, an interface to the e-file is necessary for the transmission of administrative and project-related metadata. PTB is currently working at full speed on the technical implementation. The resulting advantages are not only the faster and easier access to the data of an invoice as well as audit-proof digital archiving, but also the shorter processing times and the associated faster invoice payments. Furthermore, PTB is simultaneously working on the technical implementation to receive and process **electronic invoices** (eInvoices).

At the end of the processing scheme is the digital certificate created by PTB which has been electronically sealed. Via the "*E-Services*" customer portal, the completed certificate from the e-file is made available to the customer digitally in human- and machine-readable form. From there, it can be downloaded and directly integrated into the customer's existing IT infrastructure. Using the certificate management system of *E-Services*, customers can then send a follow-up order directly for an existing certificate, if desired.

In addition to the interfaces between e-services, e-files, order processing (including seals and invoice systems) mentioned above, PTB is at the same time identifying and defining future interfaces which are arising out of the further technological development of individual infrastructures of PTB's customers. In concrete terms, PTB is, for example, working on an interface to the European Metrology Cloud which will allow enterprises to order PTB's services in the future via a completely digital process using the instrument data that is saved there. The **Metrology Cloud** is an infrastructure which has been developed by PTB for the digital transformation of processes in QI. Its foundation is a metrology core platform at each partner which is based on trust and is to support and streamline regulatory processes by merging existing infrastructures and databases and being a central contact point for all involved parties. Within this quality infrastructure, reference architectures as well as technology- and data-driven digital services for legal metrology will be

developed. A key feature of the Metrology Cloud is the consistent use of distributed databases on the basis of distributed ledger technology, such as is used for blockchains. This ensures the protection of the data against manipulation and falsification. In particular, rather than storing data centrally, it remains at each respective partner's location. For example, a measuring device manufacturer can grant the responsible authorities access to the necessary data from its infrastructure via the Metrology Cloud. At the same time, automated digital processes can be set up with the data as so-called "smart contracts". The prototype has continuously been developed further during the last two years. Thanks to this, an initial microgrid of Metrology Cloud nodes has already been launched with the first international partners and Metrology Cloud nodes have been distributed to national stakeholders.

Up until now, digital processes for verification sequences have been implemented in the Metrology Cloud which enable a completely digital processing for the exchange of documents and software. Now, digital processes are being newly developed for calibration orders. PTB is planning the first internal trial for the exchange of DCCs via the Metrology Cloud in the spring of 2021. This trial will later form the basis for the development of a more general sample process for digital order flow between calibration laboratories and their customers in the Metrology Cloud. In the future, when an order is transmitted to PTB via the Metrology Cloud, the digital certificate will also be provided this way.

Designing the building blocks in such a way that an interlocking digital process (from customer data to order processing, documentation and issuance of certificates) emerges – this is a key objective of PTB's internal digital transformation process. In this process, the existing work and organization processes of PTB are also under consistent scrutiny and are being efficiently digitally transformed.

PTB is an essential element of the national quality infrastructure (QI) and is networked with other QI stakeholders, especially for metrological services. Together, they make up the foundation for trust in products and services and are guarantors of our economic success. The challenges and opportunities which are arising for PTB through the digital transformation apply in a similar way to QI as a whole: New types of products and services must be handled; digital processes and tools offer new multifaceted opportunities; and the established approaches must be examined. Metrology forms an essential basis for this and provides the prerequisites for many of the necessary changes.

PTB is actively tackling these challenges together with other QI stakeholders in the "QI-Digital" project. Based on a comprehensive research and implementation agenda, concrete case studies were defined and are now being jointly implemented. PTB is purposefully relying on its competence and previous work, is developing these further and is supplementing them with its partners in QI-Digital to create an interoperable digital QI. PTB's work takes all of the essential digital infrastructure systems and processes for metrological aspects in QI into account:

- the joint further development of digital certificates based on the DCC developed by PTB and the initiated work on a D-CoC;
- the further development of the Metrology Cloud into a "QI-Cloud" for digitally transformed processes in QI;

- the development of a "Digital QI Toolkit" for the digital transformation of PTB's international consultancy and collaboration work on the topic of quality infrastructure.

Here, one of the main challenges which "QI-Digital" faces is the development of an interoperable, digitally transformed quality infrastructure.

In summary, it can be said that PTB is consistently and vigorously applying its research and development work to the topic of the digital transformation of metrological services within PTB and in the entire quality infrastructure system. These activities are motivated by PTB's aim to ensure that the German metrology infrastructure continues to make a decisive contribution to Germany's innovative strength in a digitalized world with networked technologies and innovative products.

Focuses of research in the digital transformation

Digital transformation in metrology leads to numerous challenges for the field, which must be met with research and development work. Examples of this include the use of digital twins as virtual measuring instruments, complex communication systems, the use of complex sensor networks and the increasing use of artificial intelligence (AI) methods. Fittingly, PTB's research activities related to digitalization are multi-faceted.

A key feature of research and development projects in the field of digital transformation is the very high degree of interdisciplinarity. It includes complex and networked technologies based on the most diverse measurement procedures which must be metrologically characterized to ensure trust. However, classical metrological approaches are increasingly reaching their limits due to the complexity and disruptiveness of technological developments. Examples of this are metrology for autonomous driving and metrology for heterogeneous sensor networks. These combine the most diverse measurement principles with complex mathematical models and statistical methods or even AI. The totality of these challenges can only be met in the long term by changing to a holistic way of thinking and working in metrology – to a "holistic" or "systems" metrology. PTB has prepared a comprehensive concept for this, which is to be implemented on the basis of new structural and organizational approaches. PTB is already responding to these developments by consistently strengthening interdisciplinary collaboration and intensifying networking with external experts.

For this reason, PTB has established the "Metrology for Virtual Measuring Instruments (VirtMet) Competence Center". Here, it carries out interdisciplinary research and bundles expertise in order to develop concrete virtual measurement procedures as well as to work on overarching questions, for example: How can the comparability of virtual and real measurements be established? Which standards are necessary for interfaces, metadata and data formats? And how can virtual experiments for complex measurement systems be handled with machine learning methods? Based on concrete application examples such as tilted wave interferometers (TWIs) or the digital twin of the Planck balance, these questions are being dealt with interdepartmentally. In the BMWi-funded GEMIMEG-II project described below, the further development of digital twins and their integration with digital calibration certifications are being pursued.

In the course of digital transformation, artificial intelligence (AI) is increasingly playing the role of a catalyst and is greatly accelerating the development of digital products and services. As application areas of AI are growing, the need for clear rules and consideration in quality infrastructure is rising. The Enquiry Commission of the German Federal Government views AI as the next step in a technological advancement driven by digitalization. A major element of this is the way in which these algorithms are developed. A classic algorithm usually transforms a previously described procedure into software. The procedure is based on mathematical, statistical or other assumptions, theories and rules. In contrast to this, the algorithm of an AI method is trained with the help of data. Another element is the very high degree of adaptability of AI methods. These, however, may lead to unrecognized training data features being unintentionally used in the algorithm. Unlike with other software, it is hardly feasible to only check the algorithm based on the source code alone. To fulfil its legal mandate in also evaluating and monitoring scientific products, instruments and methods which include AI elements, PTB is building up the related competences. Especially in the field of medicine, PTB already has an excellent combination of domain knowledge, mathematical expertise and networking with experts at its disposal.

PTB has already developed concrete methods such as for the assessment of AI robustness and the quality of AI results. Also, PTB has published initial reference data such as the "PTB-XL" data set and strengthened the topic of "uncertainty and machine learning" through a new professorship at the TU Berlin. On this foundation, an internal "Metrology for Trust in AI ("*Metrologie für Vertrauen in KI*") Competence Center" is being set up which will fan out far beyond the field of medicine with expertise, method development and "good practices". An encompassing AI strategy will further define its orientation and work.

Specifically, the new competence center will address the lack of structured processes as well as the lack of a quality infrastructure for an objective, verifiable and reproducible validation of AI technologies. PTB is therefore working on defining objective evaluation methods to assess the quality of algorithms for machine learning; developing procedures for the provision of reference data together with medical experts; and collaborating on norms and standards for quantifiable and verifiable data quality criteria. In doing so, PTB is also pursuing the goal of meeting its legal tasks to ensure confidence in measurement procedures and methods in medicine also in the long term. To this end, PTB is specifically applying its many years of experience with measurement technology as well as in the development of virtual measurements.

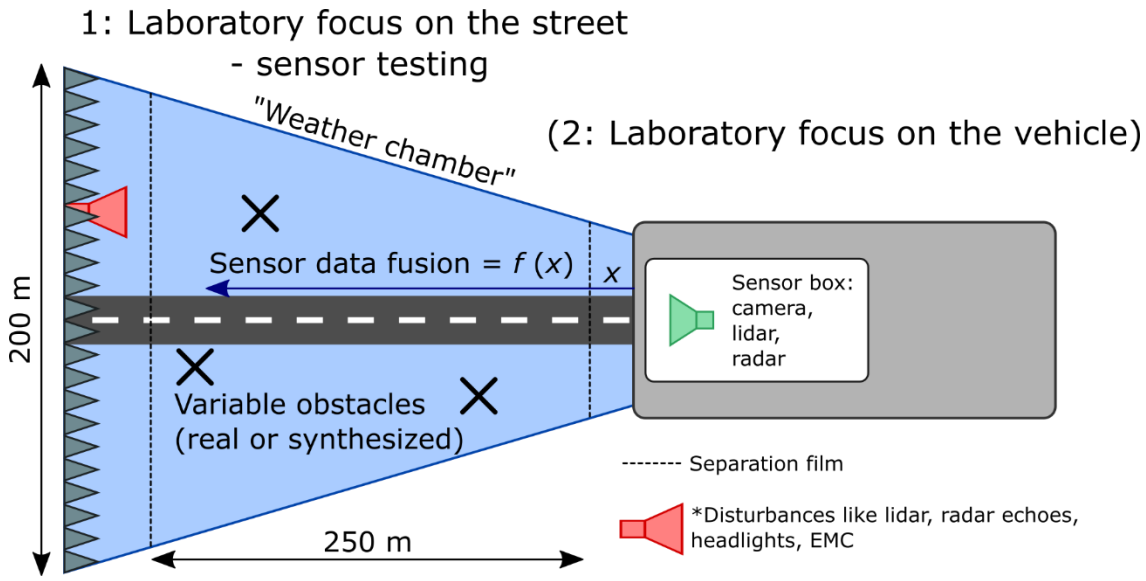

Figure 2: Principle sketch of a section of the ADAS test center

A concrete example of the complexity of networked systems is autonomous driving. In the process of the product approval of automotive components, a wide variety of test procedures are already being used today (e.g. mechanical and electric tests, climate tests). However, these are carried out for the most part at the component level and in isolation, i.e. neither in the actual assembly situation in the vehicle nor in the actual sensor system network. Particularly in the case of perception sensors of a car, the installation situation of the sensors and as well as their interaction in the representation of the environmental situation are of enormous importance for the functionality of autonomous driving. That is why it will be necessary in the future to test the entire network of ADAS (Advanced Driver Assistance Systems) components, including the applied AI methods, in its actual operation state – in addition to the component validation that is already standard today. It is completely unclear how such a holistic conformity assessment of a vehicle with ADAS functions could be realized at this time. In accordance with the ADAS strategy "Sense – Plan – Act", PTB is building on its current competences to contribute to achievements in the field of perception sensors ("sense"). A characterization and calibration of the sensor system is to be realized at a testing center that is yet to be developed. This center is to provide appropriate conditions for each type of sensor – meaning in high-frequency ranges (radar) and optical spectral ranges (lidar and cameras) – and/or even be in a position to be able to simulate traffic situations for the vehicle in a suitable manner in order to simultaneously test the driving function, if necessary. Furthermore, weather, climate and other environmental conditions of the vehicle should be definable in order to also measure these influences in a reproducible and quantifiable metrological manner.

In the industrial context, digital transformation is understood to mean, among other things, standardization and automation in sensor data handling. PTB is specifically addressing the resulting issues within the framework of cooperation projects. For example, the merging of measurement data to determine plant conditions, key data, process optimization potential, etc. is being investigated in the EU-funded project "Metrology for the Factory of the Future" (Met4FoF) and in the project "AAS-based modelling for the analysis of variable CPS" (FAMOUS) by developing methods from a metrological point of view. In terms of automated evaluation of measurement data, a

machine-interpretable description is essential. In particular, semantic concepts for metrologically meaningful time series and data quality models that go beyond pure measurement uncertainty are therefore being developed in the "Safe and robust calibrated measurement systems for digital transformation" (GEMIMEG-II) project, in the "Communication and validation of smart data in IoT networks (SmartCom)" project and also in the BMBF FAMOUS project. The extent to which redundant information in homogeneous sensor networks can be used for new calibration procedures is also being investigated.

The BMWi's GEMIMEG-II flagship project deals with the overall challenge of successfully and legally transforming the secure and robust communication of data, information and certificates in quality infrastructure processes digitally. The aim is to achieve secure, uninterrupted and legally compliant end-to-end availability of calibration information and data quality. Within the scope of the project, PTB is taking on sub-project management on aspects of generation, distribution and the application of digital calibration certificates (DCCs). Addressing the handling of DCC data as well as the handling of data extracted from DCCs under consideration of metrological traceability are also research topics. Furthermore, an adaptable digital twin concept (DT) with a higher predictability than is the case with the DTs up to now will be developed on the basis of the DCC. A further element of PTB's responsibilities in this project is the development of methods to automatically determine the quality of data (QoD). In this context, a semantic data model for a machine-interpretable description of data quality in different types of sensors (e.g. single sensors, MultiX, AI- and model-based sensors) is being elaborated. The resulting findings will lead to a methodology for using measured values and QoD information as input variables for the DT based on information from a DCC. Developed methods will flow into existing software projects or form packages of its own. For the implementation, an open-source publication adapted to current methods of software development is aimed at.

Furthermore, PTB will contribute in GEMIMEG-II to the development of a viable communication infrastructure for the networking of massive sensor networks among each other as well as to external data sources. PTB's existing expertise in the development and the application of traceable measurement methods for network and transmission quality will be brought in in this regard. A special focus rests on the development of self-forming and self-correcting wireless systems and optimizing network infrastructure. Methods for load distribution, self-optimization and self-organization, e.g. in 5G campus networks, are being investigated for this. This work on new communication systems in GEMIMEG-II is being complemented by PTB's participation in the regional project "*5G-Region Braunschweig-Wolfsburg*". At this real-world 5G laboratory, PTB is working on the reliability and comparability of quality measurements.

Summary and outlook

Metrology for the digital transformation of the economy and society is and will remain a topic with many challenges and opportunities for PTB. The pandemic situation has confirmed that PTB has chosen the right path, strengthened the developments and helped new ideas to take root even faster.

In the field of metrological services, the interlinking of digital solutions and processes is playing an important role to enable efficient and effective use of the opportunities arising from

digitalization. PTB has therefore launched a "Digital Workflow for Metrological Services" ("*Digitaler Workflow für metrologische Dienstleistungen*") project group which is actively promoting this development.

All quality infrastructure is being challenged by the digital transformation of the economy and society. PTB has laid the foundation for digital certificates and digital processes. In coordination and cooperation with other quality infrastructure stakeholders, PTB is developing this work further into interoperable digital QI which can also promote innovation in the future while ensuring trust and security at the same time: QI-Digital.

Trust in data is a key element of a successful and sustainable digital transformation. With its participation in national and international committees and by drafting data models and digital technologies, PTB has laid the foundation for trust in metrological data. This work is continually being expanded and developed further. In the future, PTB will also further expand its activities in research data management, in the development of standards for (meta)data and the uniformity and comparability of data in digital infrastructure.

The core objective "Also in a digitalized world will PTB be committed to ensuring uniformity in metrology" also includes artificial intelligence (AI) methods. That is why PTB is occupied to an increasing degree with evaluation methods for AI, assessment of data quality, reference data and benchmarks. In the future, AI will be a core competence in metrology. PTB is laying the foundation for this now.