

Systems metrology

Metrology for a new technological paradigm: goals, challenges and applications

1. Introduction

Today, metrology faces new challenges in a highly interconnected world shaped by technological advancements. Energy grids, personalized medicine, autonomous vehicles, industry IoT, environmental monitoring networks – all of them have in common that they are increasingly based on sensor systems rather than individual sensors. These technological advancements have led to highly connected systems of sensors (often “low-cost”) generating large amounts of heterogenous data that require

disruptive technologies, e.g., machine learning for processing. Metrology needs to adapt to those dynamic, data-intensive interconnected systems. The field of Systems Metrology aims to characterize such systems of sensors and processing layers and to establish a foundation for their metrological quality assurance to provide reliability, safety and comparability.

2. Challenges

We identify three main challenges within the field of systems metrology. Overcoming these is crucial for creating trust in the reliability and security of networked systems despite the issues of uncertainty, heterogeneity and large amounts of data, which in turn is vital for maintaining a scientific basis for decisions relevant to society and industry.

Challenges

Traceability in sensor systems

A systemic approach to sensor networks introduces additional complexity, but at the same time additional information enables new approaches to traceability.

Uncertainty quantification

Traditional uncertainty frameworks such as the classical GUM frameworks do not suffice for determining uncertainties in systems that involve non-trackable data fusion and data processing. Complex system outputs arising from, e.g., ML or human-as-a-sensor-approaches need novel methods to determine relevant (sub-)parameters and their uncertainties.

Quality assurance of black box models

Complex networks or systems where classical metrological approaches such as traceability or uncertainty quantification are (not yet) available are treated as black boxes for which quality assurance approaches need to be developed.

Actions to address the challenges

Innovative calibration methods

Single (low-cost) sensors benefit from the extra information of sensor systems (self-calibration, in-situ calibration). Quality assurance for networks can be maintained even under dynamic conditions by techniques such as co-calibration, uncertainty-aware interpolation and outlier detection. Heterogenous data sources bring redundancy and provide flexible methods to ensure reliable results under varying conditions, e.g., by sensor fusion.

➔ see project P1

Advanced uncertainty evaluation beyond GUM

A hybrid approach that combines simulations with empirical data enables comprehensive uncertainty evaluation. Evidence-based methods capture real-world variations pragmatically, while AI-driven modeling expands quantification possibilities.

➔ see project P2

Black box testing of safety, trustworthiness & reliability

As machine learning is often used for processing and controlling the multitude of measurement data generated in large-scale networks, metrological methods (such as “golden” reference and test datasets, as well as scenario driven approaches) to assess the intended functionality and safety of technologies involving artificial intelligence need to be developed. Appropriate metrics to evaluate their reliability quantitatively require a metrological basis.

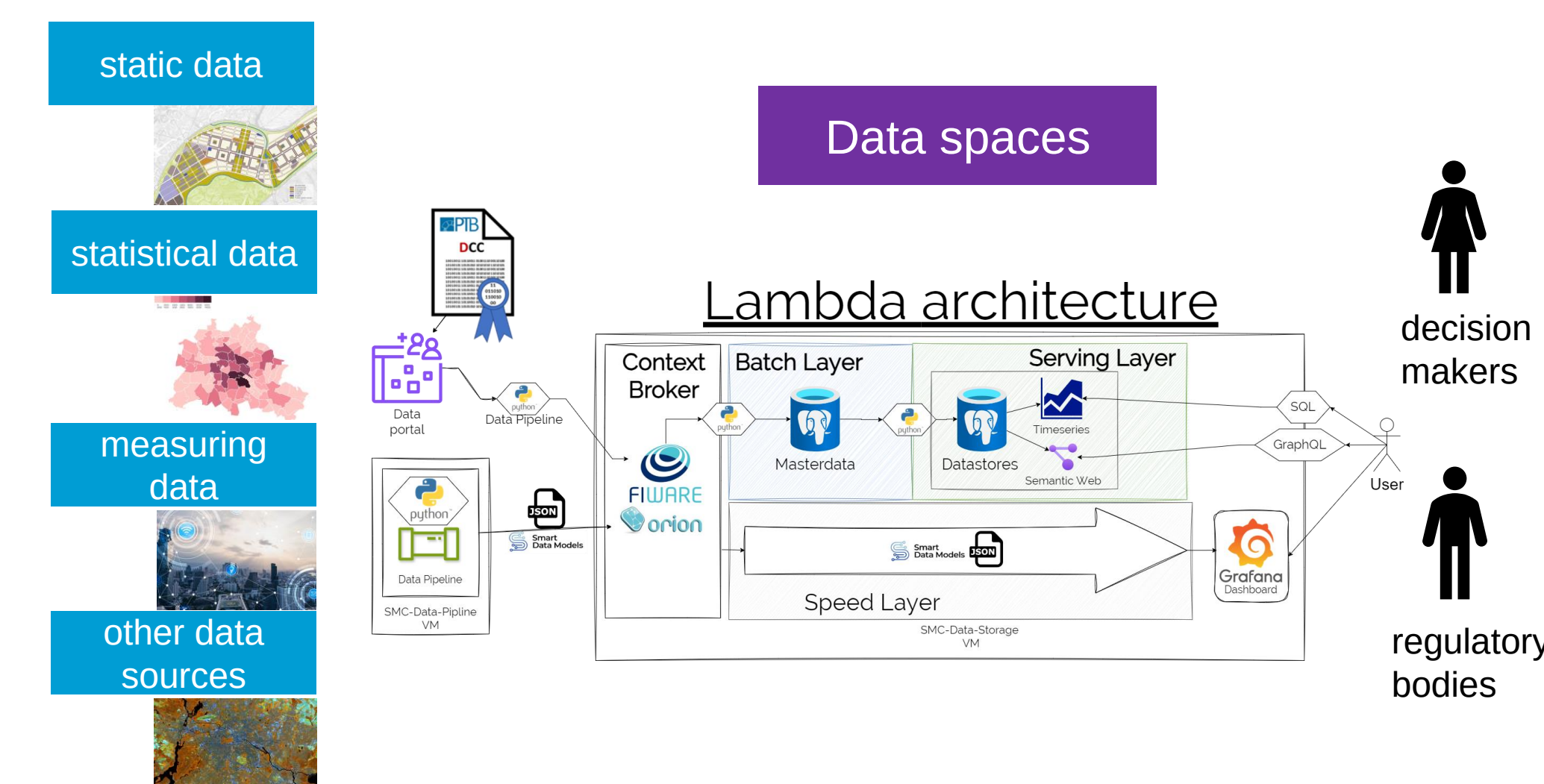
➔ see projects P2 and P3

3. Solutions - Methods

Digital Infrastructures for sensor networks P1

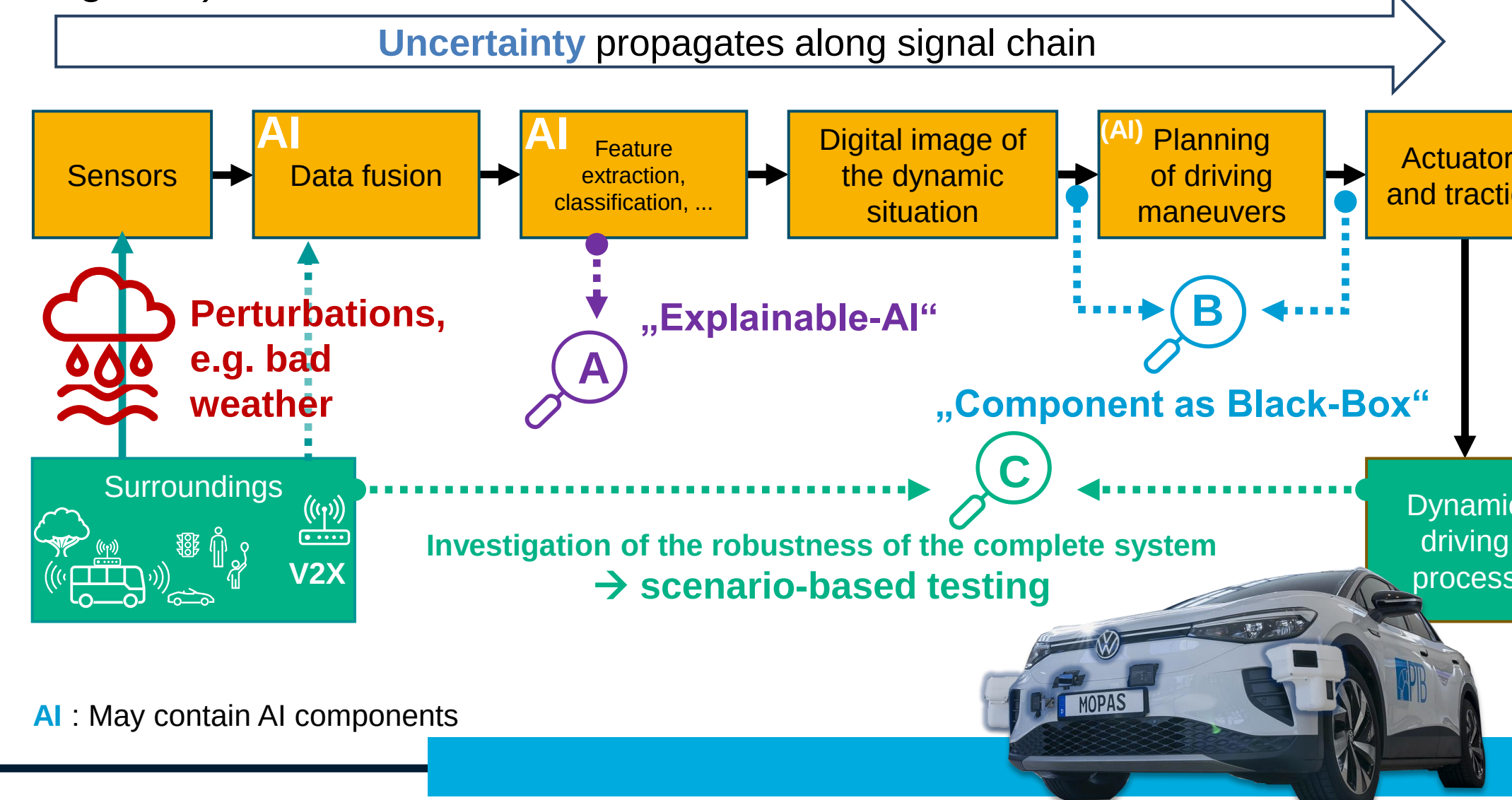
Systems Engineering Lifecycle for Data Management Architectures:

The integration of stakeholder requirements with metrological metadata leads to a better reusability of FAIR-complied data. This approach is first applied in energy data management. Building on this foundation, a smart city data infrastructure testbed will provide a controlled environment to validate the integration of metrology into complex urban data ecosystems.



Scenario-based testing of highly automated vehicles P2

The approval of highly automated vehicles necessarily places high demands on safety validation. In addition to the challenges of testing individual AI-based components, the complete system must be validated due to complex interactions. This can be addressed by scenario-based tests as part of the type approval of these vehicles. The development of measurement methods for determining evidence-based system limits and the investigation of the influence of sensor uncertainties on the system are central research topics in systemic metrology. The research vessel MOPAS (Mobile Platform for Automotive Sensor Network Testing) is PTBs primary test subject for investigating system limits under adverse conditions (rain, fog, etc.).



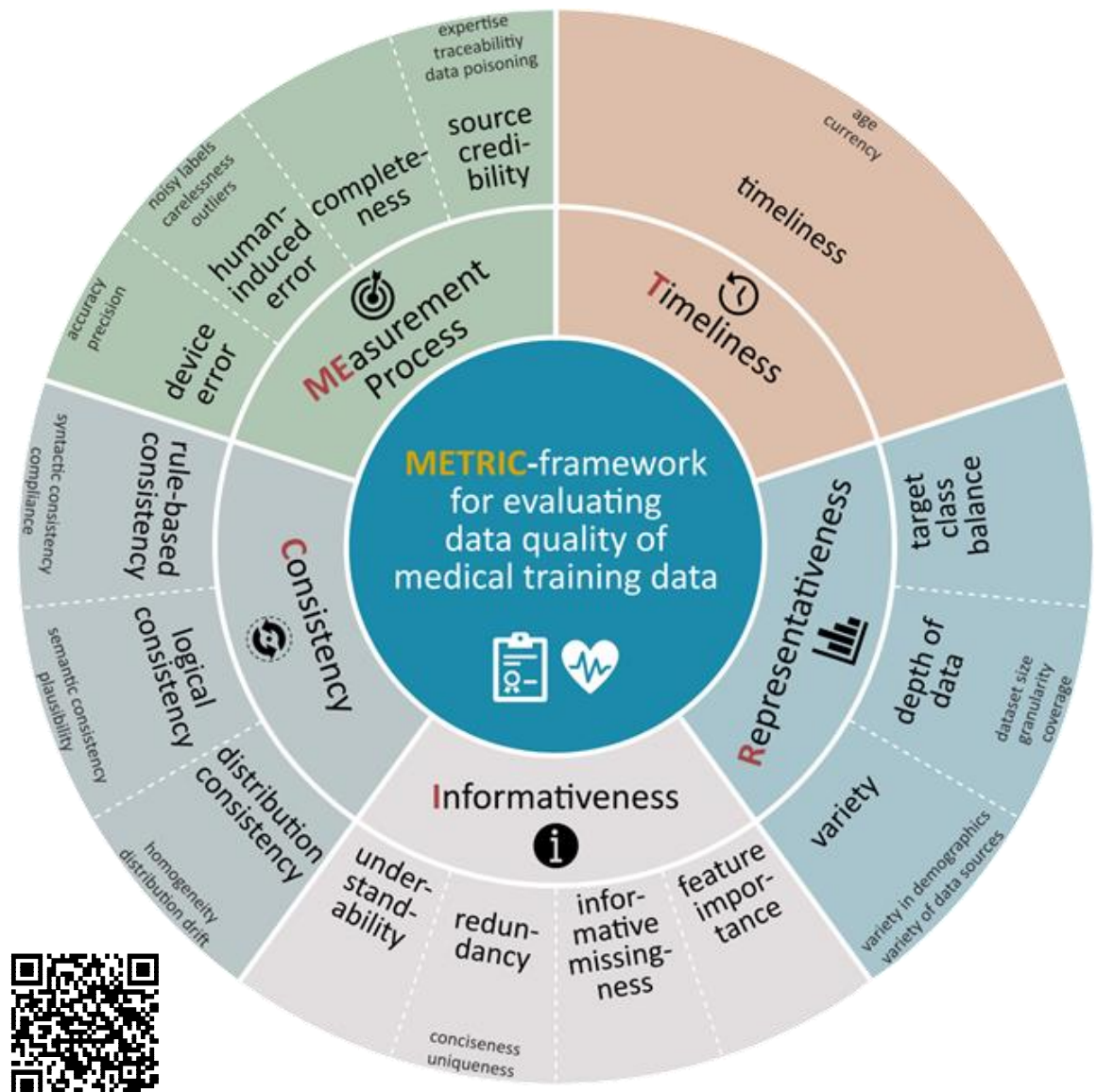
AI : May contain AI components

Quality assurance of trustworthy AI in medicine P3

Systematic evaluation of ML data using the METRIC-framework

Personalized medicine is a major application for systems metrology due to the highly interconnected and complex nature of the human body. Currently, the implementation of artificial intelligence is transforming the healthcare domain since it can help to recognise illnesses earlier, provide people with better care and reduce healthcare expenditure. However, widespread use will heavily depend on whether confidence in these systems can be built.

Due to their black box nature, one of the main ways to establish quality assurance for AI systems is to evaluate and curate training and test data. To that end, PTB has proposed the **METRIC-framework** to enhance the development of trustworthy AI medical devices. It can be utilized to **systematically assess training datasets** during audits or conformity assessment, to **establish reference datasets**, and to **guide the design of test datasets**.



4. Conclusion

As sensor networks become increasingly interconnected, systems metrology aims to ensure their traceability, uncertainty quantification and quality assurance in general across different application domains from energy management to autonomous systems and healthcare. The integration of metrological principles with advanced digital infrastructures, scenario-based testing, innovative calibration methods and the evaluation of data quality build a robust foundation for reliable measurements in networks.

5. References

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