Globalization, technological advances and societal trends are reflected in manufacturing by larger and more complex products, individualization and smaller lot sizes, tighter tolerances as well as the pursuit of shorter cycle times, higher degree of automation and resilience, improved cost-efficiency and sustainability. Cyber-Physical Production Systems (CPPS) reacting to these requirements lead to metrology becoming a indispensable enabler to provide synchronization between real world systems and virtual models required to implement adaptive automation and subsequent control loops.

This thesis introduces and investigates the Coordinates as a Service (CaaS) paradigm. It aims at making available the benefits of a virtual reference coordinate frame based on multiple, heterogeneous Large-Scale Metrology (LSM) instruments to applications constituting CPPS and relying on ubiquitous spatial synchronization. Moreover, the servitization concept allows for the separation of coordinates as provided information from the underlying measurement instruments.

The course of research commences with the introduction of a novel, artifact-free method to register the local coordinate systems of heterogeneous LSM instrument to provide a common, global coordinate system. Following the unification on physical level, an abstraction on interface level using a functional, technology-independent model for the individual LSM instruments and standardized Internet of Things (IoT) protocols is developed. To further achieve the amalgation of necessary information and data flows and their integration into the shop floor's infrastructure, a reference architecture for CaaS is elaborated using a decomposition into individual microservices as approach to satisfy the requirements of modern manufacturing IT. Adhering to the service-oriented design, the individual instruments are considered as resources of CaaS, such that an approach to resource management based on descriptive models and a novel metric is investigated.

To validate the outcome of the individual design cycles, a CaaS reference system using laser trackers, indoor GPS and ultrawideband systems as well as a machine tool is implemented at WZL's laboratory for Metrology, Assembly and Robotic Systems. The implementation is accompanied by the elaboration of a reusable multi-layer IT architecture. Both the CaaS reference system and IT architecture are used in reference applications, concluding a successful validation.

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Virtual Reference Frame Based on Distributed Large-Scale Metrology Providing Coordinates as a Service

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ERGEBNISSE AUS DER PRODUKTIONSTECHNIK

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Virtuelles Referenzkoordinatensystem auf Basis verteilter großvolumiger Messsysteme als Dienst

Von der Fakultät für Maschinenwesen
der Rheinisch-Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades eines
Doktors der Ingenieurwissenschaften
genehmigte Dissertation

vorgelegt von

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Preface

Science is done by people
Wissenschaft wird von Menschen gemacht
Werner Heisenberg, 1969

This thesis emanates from my work as a research associate at WZL | RWTH Aachen University, namely at the Chair of Production Metrology and Quality Management.

Firstly, I would like Prof. Robert H. Schmitt for the opportunity to undertake a PhD and his confident support along the course of research as well as the development of a scientific career. I am also grateful that Prof. Michael Heizmann abetted my work by acting as co-supervisor.

Many aspects of this thesis are reflected within the LaVA project (Large Volume Applications, contract 17IND03 of the European Metrology Programme for Innovation and Research – EMPIR). The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States. Working in this project and its international community has always been very enjoyable, especially when hosting 3DMC.

Working at WZL would not have been such a pleasure without numerous colleagues and friends not only sharing a common scientific vision but also many leisure activities. I am very thankful for the opportunity I had to collaborate and eventually lead a research group in such a great team. Moreover, I would like to express special thanks to all the technical and administrative staff at WZL supporting the scientific activities.

In the context of this thesis, I would like to gratefully honor the support of Matthias Bodenbenner, as well as during his time as student assistant and later as critical reviewer of the very first manuscript. This thankfulness extends to Dominik Wolfschläger for again a thorough review and many critical discussions. Last but not least, I thank Philipp Dahlem and Martin Peterek for many years of collaboration, support, shared offices and special friendship.

The foundation for this PhD journey was laid by the persisting backing of my family, above all my parents. I am very grateful to have experienced such an untroubled and promoting childhood. Finally, I experienced an immeasurable support from my wife Ann-Kathrin that simply can neither appropriately nor comprehensively be summarized in a few words.

Aachen, September 2021 — Benjamin Montavon

Abstract

Globalization, technological advances and societal trends are reflected in manufacturing by larger and more complex products, individualization and smaller lot sizes, tighter tolerances as well as the pursuit of shorter cycle times, higher degree of automation and resilience, improved cost-efficiency and sustainability. Cyber-Physical Production Systems (CPPS) reacting to these requirements lead to metrology becoming a indispensable enabler to provide synchronization between real world systems and virtual models required to implement adaptive automation and subsequent control loops. Novel paradigms, especially in assembly, imply a mobilization of resources such as robots and subsequently require an ubiquitous reference coordinate frame taking over the role of fixed monuments to maintain stable processes and account for kinematic inaccuracies.

This thesis introduces and investigates the Coordinates as a Service (CaaS) paradigm adopting the methodology of Design Science Research. It aims at making available the benefits of a servitized, virtual reference coordinate frame based on multiple, heterogeneous Large-Scale Metrology (LSM) instruments to applications constituting CPPS and relying on ubiquitous spatial synchronization.

The course of research commences with the introduction of a novel, artifact-free method to register the local coordinate systems of heterogeneous LSM instrument to provide a common, global coordinate system. Following the unification on physical level, an abstraction on interface level using a functional, technology-independent model for the individual LSM instruments and standardized Internet of Things (IoT) protocols is developed. To further achieve the amalgation of necessary information and data flows and their integration into the shop floor's infrastructure, a reference architecture for CaaS is elaborated using a decomposition into individual microservices as approach to satisfy the requirements of modern manufacturing IT. Adhering to the service-oriented design, the individual instruments are considered as resources of CaaS, such that an approach to resource management based on descriptive models and a novel metric is investigated. The approach deliberately allows to defer this task to a superordinate planning system if necessary.

To validate the outcome of the individual design cycles, a CaaS reference system using laser trackers, indoor GPS and ultrawideband systems as well as a machine tool is implemented at WZL's laboratory for Metrology, Assembly and Robotic Systems. The implementation is accompanied by the elaboration of a reusable multi-layer IT architecture. Both the CaaS reference system and IT architecture are used in reference applications, concluding a successful validation.

Globalisierung, technologischer Fortschritt und gesellschaftliche Trends spiegeln sich in der Produktionstechnik durch größere und komplexere Produkte, Individualisierung und kleinere Losgrößen sowie steigende Toleranzanforderungen wider. Zusätzlich werden kürzere Zykluszeiten, ein höherer Automatisierungsgrad, höhere Kosteneffizienz sowie stärkere Resilienz und Nachhaltigkeit gefordert. Cyber-physische Produktionssysteme (CPPS) als Antwort auf diese Anforderungen weisen der Messtechnik einen neuen Stellenwert als unverzichtbarer Enabler zur Synchronisation virtueller Modelle und realer Systeme zu. Dies wird insbesondere in der Realisierung von Regelungssystemen für adaptive Automatisierungsanwendungen deutlich. Neue Paradigmen, insbesondere in der Montage, implizieren die Mobilisierung von Ressourcen wie Robotern und setzen dementsprechend den Rückbezug auf ein ubiquitäres, globales Referenzkoordinatensystem voraus. Dieses übernimmt die Rolle von Fixpunkten und dessen Implementierung ist entscheidend zur Erreichung stabiler Prozesse und Kompensation kinematischer Abweichungen.

Die vorliegende Arbeit definiert und untersucht Coordinates as a Service (CaaS) als neues Paradigma. Das Ziel von CaaS ist es, ein verdienstliches, virtuelles Referenzkoordinatensystem auf Basis mehrerer, heterogener, großvolumiger Koordinatenmesssysteme für die ubiquitäre, räumliche Synchronisation in CPPS bereitzustellen. Die Forschungsarbeit folgt dabei der Methode des Design Science Research.

Die Untersuchungen setzen bei einer neuartigen Methode zur Registrierung der lokalen Koordinatensysteme der individuellen Messsysteme an, welche ohne kalibrierte Referenzkörper auskommt. Der physikalischen Zusammenfassung zu einem globalen System folgt die Abstraktion der Interaktion durch die Entwicklung eines technologieunabhängigen, funktionsorientierten Modells und dessen Verknüpfung mit standardisierten IoT-Protokollen. Zur Aggregation der Informationen und Datenflüsse sowie zur Bereitstellung von CaaS als infrastrukturelle Komponente des Shopfloors wird daraufhin eine Referenzarchitektur für CaaS entwickelt. Hierzu wird eine Dekomposition des Gesamtsystems in sogenannte Microservices vorgenommen, um die Systemanforderungen zu berücksichtigen und die Nutzung moderner, mehrschichtiger IT-Strukturen zu ermöglichen. Dem Ansatz der Verdienstlichung folgend werden die Messsysteme als Ressourcen aufgefasst, weswegen im nächsten Schritt ein Ansatz zur Ressourcenverwaltung erforscht wird. Dieser basiert auf deskriptiven Modellen und wendet eine in dieser Arbeit neu entwickelte Metrik an, während er explizit die Möglichkeit zur Delegation an ein übergeordnetes Planungssystem beibehält.

Zur Validierung der Forschungsergebnisse zu den einzelnen Teilfragen im Gesamten wird ein Referenzsystem implementiert, welches mehrere Laser Tracker, ein indoor GPS, ein Ultrabreitand-Lokalisierungssystem sowie eine Werkzeugmaschine einbindet. Im diesem Zuge wird auch eine wiederverwendbare, mehrschichtige IT-Infrastruktur entwickelt. Sowohl das CaaS Referenzsystem als auch letztgenannte Infrastruktur werden in mehrere Anwendungen eingebunden und schließen somit die Validierung erfolgreich ab.

Contents

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List of Symbols

Symbol	Typ. Unit	Description
n_{LSM}	-	Number of present Large-Scale Metrology instruments
$n_{consumer}$	-	Number of service consumers
$\mathcal{S}$	m^3	Shop floor volume
$\mathcal{M}_{(i)}$	-	i-th Large-Scale Metrology instrument
$\mathcal{C}$	-	CaaS consumer
$\mathcal{E}$	-	Mobile entity
$\mathcal{L}$	-	Metrological capability
$\mathcal{W}$	m^3	Working volume
Σ_i	-	Coordinate system, index 0 refers to a global coordinate system
$\boldsymbol{p}_i$	m	Position expressed in coordinate system i
$\mathbf{V}_i$	m^2	Covariance matrix expressed in coordinate system i
$\mathbf{R}_i$	-	Rotation matrix from Σ_i to Σ_0
$\boldsymbol{T}_i$	m	Translation vector from Σ_i to Σ_0
μ_i	-	Scale factor from Σ_i to Σ_0
a_i	-	1^{st} quaternion component of rotation from Σ_i to Σ_0
b_i	-	2^{nd} quaternion component of rotation from Σ_i to Σ_0
c_i	-	3^{rd} quaternion component of rotation from Σ_i to Σ_0
d_i	-	4^{th} quaternion component of rotation from Σ_i to Σ_0
$\mathcal{P}_i$	mixed	Set of transformation parameters from Σ_i to Σ_0
$\mathcal{V}_i$	mixed	Covariance associated with $\mathcal{P}_i$
$\mathbf{S}_0$	m^2	Covariance contribution of coordinate transformation
$\mathbf{V}_0^*$	m^2	Combined covariance of a transformed coordinate
v_0	m	Square-root of the trace of $\mathbf{V}_0$

Symbol	Typ. Unit	Description
s_0	m	Square-root of the trace of $\mathbf{S}_0$
v_0^*	m	Square-root of the trace of $\mathbf{V}_0^*$
$\boldsymbol{p}_i'$	m	Reference position measured corresponding to $\boldsymbol{p}_i$
$\mathbf{V}_i'$	m^2	Covariance associated with $\boldsymbol{p}_i'$
$\mathbf{O}_j$	-	Rotation matrix reflecting an artifact's orientation at location j of a measurement strategy
$n_{locations}$	-	Number of locations in a measurement strategy
$n_{constraints}$	-	Number of geometric constraints of an artifact
$\mathbf{u}_k$	m	Geometric constraint k of an artifact
l	m	Geometric length constraint/bar length
r_j^2	m^2	Residual at measurement location j
σ_j^2	m^2	Minimization weight at measurement location j
χ^2	-	Chi-squared sum as minimization objective
$\mathcal{P}_i^{\mathrm{opt}}$	mixed	Transformation parameter set at optimization minimum
$\mathcal{V}_i^{\mathrm{opt}}$	mixed	Covariance of transformation parameter set at optimization minimum
$\mathcal{P}_i^*$	mixed	Predefined transformation parameter set for simulation purposes, including a_i^*, b_i^*, c_i^*, d_i^* and $\boldsymbol{T}_i^*$ accordingly
$\alpha_{x,y,z}$	rad/°	Euler angles of rotation
$n_{samples}$	-	Number of samples in a Monte Carlo simulation
$n_{converged}$	-	Number of converged samples
$\bar{\sigma}_i$	m	Preset characteristic standard deviation in Monte Carlo simulation
$\mathcal{W}^*$	m^3	Virtual working volume of simulation
w	m	Characteristic length of virtual working volume
$\varepsilon_{i,j,k}$, $\varepsilon'_{i,j,k}$	m	Statistical contributions drawn from a normal distribution for instrument i at location j in simulation sample k

Symbol	Typ. Unit	Description
$\mathcal{P}_{i,k}^{\mathrm{opt}}$	mixed	Transformation parameter set at optimization minimum for simulation sample k
$\mathcal{V}_{i,k}^{\mathrm{opt}}$	mixed	Covariance of transformation parameter set at optimization minimum for simulation sample k
NDF	-	Number of degrees of freedom
$\mathbb{I}_{(i)}$	-	Instrument microservice belonging to $\mathcal{M}_{(i)}$
$\mathbb{M}_{(i)}$	-	Instrument modeling microservice belonging to $\mathcal{M}_{(i)}$
$\mathbb{U}$	-	User microservice
$\mathbb{E}$	-	Entity management microservice
$\mathbb{A}$	-	Allocation microservice
$\mathbb{P}$	-	Planning microservice
$\mathbb{C}$	-	Consumer microservice
$\mathbb{X}$	-	External microservice
$\mathbb{T}$	-	Thing management microservice
Δt	s	Allocation time span delimited by two dates
$\hat{\boldsymbol{p}}$	m	Planned position of a measurement
$\hat{\boldsymbol{n}}$	m	Expected normal vector of mobile entity during measurement
$\hat{\boldsymbol{q}}$	m/s	Expected velocity of mobile entity during measurement
$\mathcal{B}$	-	Boolean coverage indication
$\mathcal{Q}$	-	Boolean angular acceptance indication
$\hat{\mathbf{V}}$	m^2	Predicted covariance
$\hat{\mathbf{S}}$	m^2	Predicted transformation covariance
$t_{measure}$	s	Time required for a measurement
t_{dead}	s	Dead time between physical measurement and devlivery via the instrument's interface
f_{sample}	Hz	Maximum sample frequency
v_{max}	m/s	Maximum velocity at which measurements can be taken
T_{min}, T_{max}	$^\circ$C	Temperature limits for environmental conditions
p_{min}, p_{max}	Pa	Pressure limits for environmental conditions

Symbol	Typ. Unit	Description
H_{min}, H_{max}	%	Relative humidity limits for environmental conditions
$\mathcal{O}$	-	Orientation measurement capability flag of mobile entity characteristics
$\mathcal{F}$	-	Target type enumeration
$\mathcal{R}$	-	Exclusive instrument use flag of mobile entity characteristics
$\mathcal{T}$	-	Traceability flag of mobile entity characteristics
$\mathcal{K}$	-	Mobility flag of mobile entity characteristics
$\frac{\partial C}{\partial t}$	€/s	Temporal cost estimation for mobile entity use
T	m	Tolerance (for example of circular feature)
Q_{MP}	%	Measurement process qualification (for example of circular feature)
U_{MP}	%	Measurement process uncertainty with 95% confidence level (for example of circular feature)
$\sigma_{diameter,max}$	m	Unexpanded uncertainty limit for diameter (for example of circular feature)
n_{points}	-	Number of circumferent measurement points (for example of circular feature)
$\sigma_{point,max}$	m	Unexpanded uncertainty limit for single point (for example of circular feature)
$\hat{H}$	m	Ranking operator
U	m	Variable uncertainty limit
Ω	-	Integral phase space metric
p_0	m	Normalization constant for phase space metric
q_0	m/s	Normalization constant for phase space metric
Γ	-	Ranking metric
U_0	m	Normalization constant for ranking metric
U_{max}	m	Upper uncertainty integration limit for ranking metric
α	-	Exponential weighting coefficient in ranking metric

Symbol	Typ. Unit	Description
γ	-	Spatial weighting function in ranking metric
e	-	Exponential function
τ	-	Integration variable
$\Delta\Gamma$	-	Ranking decrease function
$\Gamma_{\mathcal{E}'}$	-	Single entity ranking metric
$\hat{H}^*$	m	Discretized ranking operator
Ω^*	-	Discretized phase space metric
$\hat{\boldsymbol{q}}^*$	m/s	Characteristic velocity
$A_{r,s}$	m^3	Subvolume of station r, s on a discretized shop floor with $1 \ldots m \times 1 \ldots n$ stations
$\mathbf{J}_{spherical}$	mixed	Jacobian of spherical to Cartesian coordinates
r	m	Spherical distance
φ	rad/°	Azimuth angle
θ	rad/°	Elevation angle
$\sigma_{r,0}$	m	Standard deviation coefficient for distance
$\sigma_{r,1}$	-	Standard deviation coefficient for distance
$\sigma_{\varphi,0}$	rad/°	Standard deviation coefficient for azimuth
$\sigma_{\varphi,1}$	rad · m/° · m	Standard deviation coefficient for azimuth
$\sigma_{\theta,0}$	rad/°	Standard deviation coefficient for elevation
$\sigma_{\theta,1}$	rad · m/° · m	Standard deviation coefficient for elevation
R_{valid}	m	Valid spherical distance range
Φ_{valid}	rad/°	Valid azimuth angle range
Θ_{valid}	rad/°	Valid elevation angle range
$\sphericalangle_{acceptance}$	rad/°	Acceptance angle
$\tilde{\boldsymbol{T}}_i$	m	Position of a transmitter
$\tilde{\mathbf{R}}_i$	-	Orientation of a transmitter
$n_{transmitters}$	-	Number of transmitters

1 Introduction to and Definition of Coordinates as a Service

Globalization, technological advances and societal trends are reflected in manufacturing by larger and more complex products, individualization and smaller lot sizes, tighter tolerances as well as the pursuit of shorter cycle times, higher degree of automation and resilience, improved cost-efficiency and sustainability [BREC17, DENK19, SALV20]. Adhering to these objectives manifests in economic benefits ranging from lower production costs and improved resource utilization over reduced scrapping and material wastage to increased efficiency of the product itself, for instance regarding components used in the aerospace and energy sectors [SCHM16]. Cyber-Physical Production Systems (CPPS) aim at fulfilling these objectives with metrology becoming an indispensable enabler to provide synchronization between real world systems and virtual models required to implement adaptive automation and subsequent control loops [MONO16]. An elucidating representative are assembly processes, potentially responsible for a significant share of manufacturing costs but reaching the limits of traditional automation if repeatability is absent due to high product variability or unstable processes [HÜTT19, TRIE20]. Novel paradigms addressing this issue imply a mobilization of assembly resources such as robots and subsequently require an ubiquitous metrological reference frame taking over the role of fixed monuments to maintain stable processes and account for kinematic inaccuracies [SCHM16, DROU18]. On the other hand, advances in information technology have fostered hardware, platforms, software and industrially matured protocols to realize complex, value adding applications with distributed computing capabilities and data sources, emphasizing the prospects of service-oriented designs for interoperability [ALFU15]. The latter is critical in CPPS considering the large number of sensors, actors and data processing requirements [SCHM18].

This thesis introduces and investigates the **Coordinates as a Service (CaaS)** paradigm (cf. Section 1.2). It aims at making available the benefits of a virtual, metrology-based reference coordinate frame and servitized sensor information (cf. Section 1.1) to applications constituting CPPS, i.e. enabling ubiquitous spatial synchronization. Thereby it extends the role and value of existing Large-Scale Metrology instruments through the shift from solitary use to their incorporation into a shop floor's infrastructure available to arbitrary applications, including a priori unknown and previously existing ones. The service-oriented approach embraces an abstraction of coordinate measurements on technology-agnostic level, allowing for interchangeable and requirement-driven use of Large-Scale Metrology instruments considering their capabilities as resource characteristics.

1.1 Motivation of a Servitized Virtual Metrology-based Reference Coordinate Frame

Increasing tolerance demands, product scales and manufacturing respectively assembly systems' volatility demand for adaptive automation and increasing the accuracy of kinematic processes (e.g. involving robots or machine tools). A possible approach is to establish self-referencing capabilities for automated systems through the integration of suitable metrology instruments [SCHÖ18]. Extending this approach from local systems to an entire shop floor or production facility, within this scope a global reference system with an adhering coordinate system is established. Consequently, it provides a physically interpretable interface to virtual systems, among others for simulation and planning [SCHM16**?** , QUIN18].

Accuracy improvement for kinematic processes can be achieved either by relying on the global reference system in a dedicated calibration sequence replacing materialized references or by instantiating a control loop incorporating the metrological in-process feedback, in both cases optionally including information of local sensors [MARO14]. This technique allows to pursue the objective of kinematic accuracy in reconfigurable, collaborative and dynamic robotic systems on the basis of the common reference coordinate system, including mobilization of the respective work pieces [SCHM11, STOR17, SCHÖ18]. Such scenarios have already been outlined over the recent years, e.g. for the assembly of aircraft structures [OBER16]. The approach is systematized and intensified in *Line-less Mobile Assembly Systems (LMAS)* building on the three core principles of a clean shop floor, mobilization of all assembly relevant resources and unrestricted resources assignment as introduced in Figure 1.1 [HÜTT19, BUCK19]. The capabilities and stability of implemented LMAS benefit from a global metrological reference through decoupling kinematic accuracy from specific automation resources, availability of a cross-resource coordinate system as well as an extended data basis for complex models linked to adhering macroscale control loops and planning strategies [BERG20, pp. 158-180].

The global availability of a metrological reference system can also also be leveraged for non-automated applications on the shop floor, i.e. substituting the temporary, local use of portable coordinate measuring systems for common dimensional measurement tasks. These again comprise assembly of large-scale parts with elevated tolerance requirements, e.g. in aerospace and shipbuilding [MUEL14, SCHM14, SCHM16], but also their manufacturing and handling involving intermediate dimensional measurements to account for instable processes and geometric deformation, especially due to thermal influences [OHLE19]. Transitioning dimensional measurements from dedicated measurement rooms to in-process, on-machine or at minimum on-shop floor solutions enables decreasing the overhead in quality assurance and shortening times for corrective cycles [SCHM16, MONO14]. Maintaining traceability, the scope of global reference systems is extended to a holistic

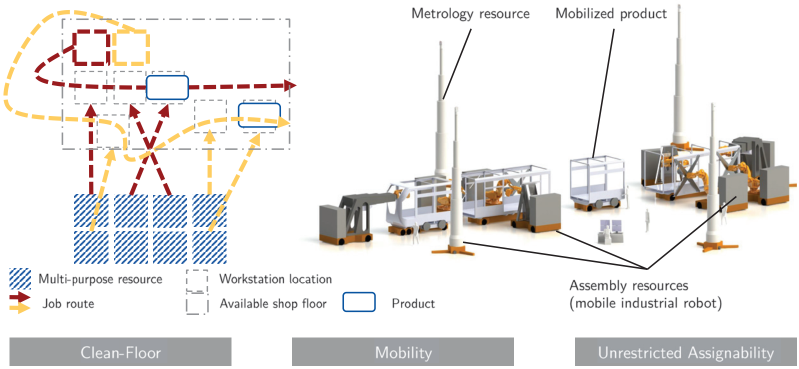

Figure 1.1: Schematic description of Line-less Mobile Assembly Systems (LMAS) by HÜTTEMANN et al. [HÜTT19]. On a clean shop floor, products and resources are fully mobile and flexibly assigned to jobs. To reduce complexity, a factory configuration in mobile stations containing specific resources is introduced. Among the latter is the availability of dimensional metrology systems, forming the link to a CaaS system. Moreover, a metrological reference frame is favorable to maintain stable processes at present mobility and reconfigurability.

perspective on the measurement process not only involving coordinate measuring systems but also additional sensors (e.g. thermometers) and information sources, eventually integrating with the concept of *information-rich metrology* which envisages improved measurement results by extensive knowledge incorporation and modeling [LEAC18].

In literature, global reference systems and their aforementioned applications conceptually evolved under the term of a *Virtual Metrology Frame*, subsuming characteristic properties: A global reference system constitutes the frame of a Cyber-Physical Production System by defining the reference coordinate system in lieu of fixtures or monuments while it is ubiquitously available and not bound to individual operations [SCHM16, p. 657]. It is virtual both in the sense of not being a materialized spatial reference and by the inherent assumption that deduced feedback to the applications relying on aforementioned frame relies on virtual models of the respective processes and measurement instruments [PERM16, BERT17].

Boundary conditions, measurement volume, uncertainty and performance requirements involved in an adequate implementation of a Virtual Metrology Frame lead to individual measurement instruments reaching their technological limits [GALE15]. Therefore it can ab initio be assumed that a cooperative approach involving multiple, heterogeneous and distributed instruments is required to satisfy the different demands of applications to a metrological reference. This assumption is reinforced by the fundamental economic aim of cost-efficiency liaised with the typical cost-performance relation of measurement systems demanding for an adaptive instrument choice. The therewith inherent complexity of the overall system in conjunction with its permanent availability characteristic and general interoperability requirements in connected production systems promote a service-oriented design [SCHM17, SCHM18]. The CaaS principle developed during the course of research adhering to this thesis aims at advancing the Virtual Metrology Frame from a coarse concept and prototype applications to an elaborated system integrated into the framework of the *Internet of Production* [BREC17, PENN19]. The users, further referred to as service consumers, are by definition arbitrary and the internal realization is abstracted through according interfaces. Consequently, all applications hitherto mentioned can be considered as potential CaaS consumers.

1.2 Introduction of the CaaS Concept and Principal Research Objectives

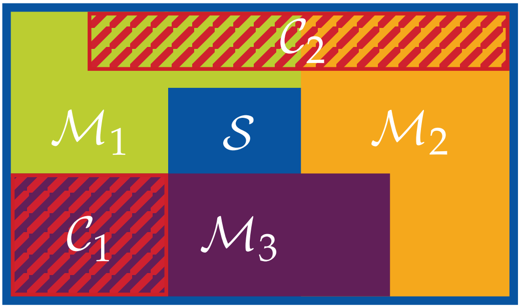

Figure 1.2: Top-View schematic of a scenario where CaaS can be applied: In a shopfloor volume $\mathcal{S}$ Consumer $\mathcal{C}_1$ requires position information measurable with instruments $\mathcal{M}_1$ and $\mathcal{M}_3$, while $\mathcal{C}_2$ operates in a volume covered jointly by $\mathcal{M}_1$ and $\mathcal{M}_2$. The assignment of instruments as resources to consumers depends on the requirements regarding the metrological capabilities.

Figure 1.2 summarizes a formalized description of the underlying application problem of CaaS: Let $\mathcal{S}$ be a bounded physical volume containing n_{LSM} individual Large-Scale Metrology instruments (Definition 1.3) $\mathcal{M}_i$ operating in the respective subvolumes $\mathcal{W}_i \subseteq \mathcal{S}$. At the same time, $n_{consumer}$ coordinate consumers (Definition 1.5) demand for position information (Definition 1.1) within a volume of application $\mathcal{C}_i$ maintaining a set of required metrological capabilities $\{\mathcal{L}_i\}$ (Definition 1.4). In an industrial scenario, $\mathcal{S}$ corresponds to the span of the shop floor and coordinate consumers are the respective applications benefiting from a virtual, metrology-based reference coordinate frame, e.g. as introduced in Section 1.1.

Definition 1.1: Position Information
Position information refers to the complete result of a 3D coordinate measurement, i.e. the position of an entity $\boldsymbol{p}$ itself with associated covariance $\mathbf{V}$ and traceability information (Definition 1.2) if applicable.

Definition 1.2: Traceability Information
Aggregate information required to relate the result of a measurement to a reference realization and documenting an unbroken chain of calibrations with their contributions to the measurement uncertainty [BIPM08, t. 2.41].

Definition 1.3: Large-Scale Metrology (LSM) Instrument
A Large-Scale Metrology instrument[a] $\mathcal{M}$ is conceived as a system utilizable to provide position information of one or multiple mobile entities within a defined volume of operation $\mathcal{W}$ in a local coordinate system Σ.

[a]Following the VIM, a *measurement instrument* is a »device used for making measurements, alone or in conjunction with one or more supplementary devices« [BIPM08, t. 3.1]. The therein recommended denomination of a measurement instrument usable on its own as measurement system is omitted throughout this thesis to avoid an overloaded use of the word *system*.

Definition 1.4: Metrological Capability
A property $\mathcal{L}$ of a measurement instrument influencing its applicability to a specific task and/or its contribution to uncertainty budget of the obtained measurement results.

Definition 1.5: Coordinate Consumer
A coordinate consumer is an application requiring position information of one or multiple mobile entities within a defined volume $\mathcal{C}$ maintaining a set of metrological capabilities $\{\mathcal{L}_i\}$.

Coordinates as a Service (CaaS) is proposed as infrastructural model where position information within $\mathcal{S}$ is exposed as a service (Definition 1.6) to coordinate consumers utilizing heterogeneous Large-Scale Metrology instruments as resources. The underlying physical principles and specific functions of the involved instruments are opaque to the users of the service, such that they uniformly interface with a global system based on technology-independent characteristics. The latter constitutes a metrology based, virtual reference frame for applications requiring position information and a set of metrological capabilities $\{\mathcal{L}_i\}$ within $\mathcal{S}$. A consumer can be an arbitrary application requiring coordinate measurements, e.g. handheld probes or components of LMAS.

Definition 1.6: Service
A service is a mechanism to enable access to one or more capabilities, where the access is provided using a prescribed interface and is exercised consistent with constraints and policies as specified by the service description, while its implementation remains opaque. The consumers of the service may demonstrate a use beyond the scope originally conceived by the provider [OASI06, p. 12].

As CaaS is a newly proposed concept, the principle research question is whether CaaS can be realized:

Can position information within a virtual reference frame defined by multiple, heterogeneous Large-Scale Metrology instruments be provided to industrial applications as a service with abstracted interface?

Before a service-oriented unification is possible on interface level, unification of the position information on a physical level is necessary. This includes the transformation from local coordinate systems, a common interpretation of measurement uncertainty and experimental procedures for estimating the parameters of involved mathematical models. The first subquestion is summarized as follows:

1. *Can position information of heterogeneous Large-Scale Metrology instruments be transformed into a global coordinate system?*

Communication protocols emerging from the field of *Internet of Things (IoT)* offer standardization in the field of machine-to-machine communication but only on a syntactic, technical interaction level, e.g. regarding aspects as addressing, encryption, encoding and authorization. The respective standards do not cover the a priori decoupled semantic problem of linking information and/or functions offered by a specific machine to a representation in the protocol incorporating domain-specific knowledge. While device profiles as for instance common in Bluetooth protocols solve this task [BLUE20], similar profiles have not yet been established in the field of Large-Scale Metrology, such that subsequent question arises:

2. *Can a model-based, protocol-agnostic interface to Large-Scale Metrology instruments be defined based on technology-independent characteristics?*

The interface definition on instrument level in contrast to an implementation as global abstraction layer avoids predetermined limitations to the topology of the architecture realizing CaaS. The latter must account for instrument metadata, resource management, measurement data transmission and any other component which will be identified as necessary to offer the proposed service, and hence directly introduces the third subquestion:

3. *Does an appropriate system architecture respecting interfaces and decomposition to implement and servitize a virtual, metrology-based reference frame exist?*

The efficient administration of the individual systems as resources is essential for an economically beneficial transition from a device-oriented to a service-oriented employment of Large-Scale Metrology instruments, driven by their typically inverse relation between operation cost and achievable uncertainty as well as capabilities required unique to subsets of the instruments available. At the same time, the service may not only interact with individual consumers, but also with groups of correlating consumers organized by a superordinate planning system (e.g. LMAS). Core objective of the resource management is to maximize service availability by optimized assignment of Large-Scale Metrology instruments, effectively minimizing the number of coordinate requests denied due occupancy of instruments with required metrological capabilities. The following question is dedicated to finding a balance between service-oriented abstraction and global efficiency:

4. *Can the individual, technologically heterogeneous instruments be managed as service resources without interacting with superordinate planning from an industrial application's perspective?*

In contrast to the guiding questions, some explicit non-objectives shall be stated to delimit the scope of research:

- Detailed development of coverage and uncertainty models for specific LSM instruments.
- Primary development and implementation of automation systems exceeding the scope of a service consumer.
- Operations planning to achieve global optimization objectives in manufacturing systems including CaaS.
- Layout optimizations for one or multiple distributed LSM instruments.
- Servitization of actor control, although analogies may be possible.
- Elaboration of models to deduce metrological requirements directly from metrology assisted assembly processes.
- Explicit implementation of services to provide further analyses based on the acquired position information, e.g. calculation of features.
- Resilience and error management strategies outside the immediate system boundaries of CaaS.
- Incrementation of throughput for inline coordinate measurements compared to a non-servitized use of measurement instruments.
- Service-discovery strategies as the awareness of the consumer for CaaS is bound to a physical volume.

A brief review on the research objectives is provided in the intermediate summaries at the end of Chapters 3 to 7.

1.3 Envisaged Service Characteristics

Supposing the principal research objectives can be answered positively and the according subtasks satisfied, the following explicit service characteristics from the perspective of a consuming application are envisaged:

- Respond to a consumer $\mathcal{C}_i$ whether position information in a required volume $\mathcal{W}_i \subseteq S$ can be provided with a set $\{\mathcal{L}_i\}$ of required, technology-agnostic metrological capabilities.
- Suggest a possible subvolume $\mathcal{W}_i$ if in the previous case no subvolume is predefined by the consumer.
- Manage concurrent requests by providing an allocation mechanism based on time periods Δt.
- Provide access to position information of individual Large-Scale Metrology instruments $\mathcal{M}_i$ in a global coordinate system Σ_0 over a unified interface.
- Possess extendability to integrate further Large-Scale Metrology Instruments $\mathcal{M}_i$ as additional resources.
- Allow for the explicit, i.e. manual allocation of a Large-Scale Metrology instrument by a consumer to account for compatibility requirements not covered by the metrological characteristics model.

Recapitulating different servitization levels in metrology introduced by SCHMITT and VOIGTMANN, visualized in Figure 1.3 and offering a conceptual framework, the provider responsibility in CaaS comprehends the sensor information level encapsulating the physical sensor, its interface and the obtained sensor value. In addition, parts of the characteristics level are included as Definition 1.1 recognizes traceability and covariance as part of position information and Definition 1.4 accounts for the instrument's contributions to the uncertainty budget. Therewith, CaaS partially covers modeling and measurement uncertainty evaluation. The provenance of a characteristic's value lies outside the immediate scope of CaaS as from the perspective of the latter this already constitutes a specific application, i.e. a characteristic providing service could be realized as consumer of CaaS. Obversely, the broadest possible application scope clearly exceeds the measurement of characteristic features when following the motivation in Section 1.1.

Another abstract framework to CaaS is provided by the *OASIS Reference Model for Service Oriented Architecture*. The principal concepts defined by the former which must be considered when designing a service oriented architecture are restated in Figure 1.4 and associated with the aspects of CaaS to be considered during its development, implementation and operation [OASI06].

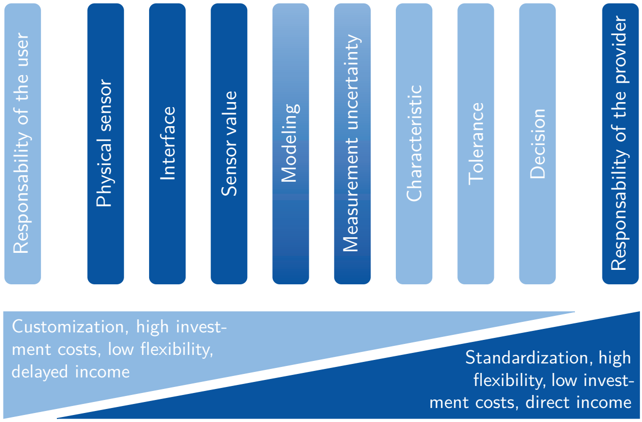

Figure 1.3: Deployment levels of sensor information as a service according to SCHMITT et al. [SCHM18, p. 396]. The levels coloured in dark blue shall be delivered for position information by the proposed service. The aspects of modeling and measurement uncertainty are partially covered as the according contributions of the Large-Scale Metrology instrument itself, but not of the entire measurement process, are encapsulated.

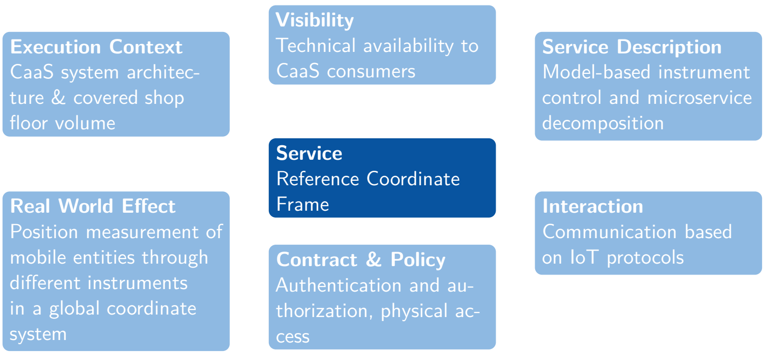

Figure 1.4: Classification of CaaS according to the *OASIS Reference Model for Service Oriented Architecture* [OASI06, p. 12].

1.4 Research Methodology and Related Thesis Structure

ULRICH follows POPPER stating that research should not originate from observations and theory but from genuine problems [ULRI81, p. 5]. Regarding the investigation of problems arising from the context of industrial applications, ULRICH furthermore derives a systematic research methodology grounding the former on fundamental research and formal sciences with explicit practical input [ULRI81, pp. 19-21]. As required by the latter, a formalized description of the underlying problem of CaaS has been deduced in the previous section where the application context is accentuated by the service concept requiring consumers as raison d'être without strictly predefining the latter and maintain a broad application scope. Moreover, its roots in information technology respectively computer sciences indicate the relevance of this domain to CaaS and the subsequent elaboration of the research questions. ULRICH also emphasizes the importance of artifacts beside hypothesis falsification when researching technical systems [ULRI81, pp. 6-7]. Both aspects are respected by the closed formulation of the principal research objective and subsequent questions, which are investigated by falsifying the according rival hypotheses through designing and implementing a reference system.

Maintaining these aspects, the research methodology of *Design Science in Information Systems* is reflected in the development of CaaS. Elaborated by HEVNER et al., »design science [...] supports a pragmatic research paradigm that calls for the creation of innovative artifacts to solve real-world problems. Thus, design science research combines a focus on software/information system artifact with a high priority on relevance in the application domain.« [HEVN10, p. 9]. A derivative methodology further incorporating aspects of agile development has been introduced by ADIKARI et al. with the *Little Design Up-Front* principle adhering to the same three cycles established by HEVNER et al. (cf. Figure 1.5) [ADIK09]:

- The **relevance cycle** relates the design research to the application domain where the initiating problem emerges, respecting the adhering organizational and technical context and defining the requirements to the design of the system. It also constitutes the environment to which it is continuously exposed and evaluated through implemented artifacts.

- The **rigor cycle** grounds the design activities to the state of the art in the application domain. The latter is embedded into the concept of knowledge base, which also comprises scientific theories and methods as well as to best-practices relevant to the design. Therefore it is not necessarily limited scientific literature. The cyclic nature of the methodology assumes an active enhancement of the knowledge base through impact and dissemination of results.

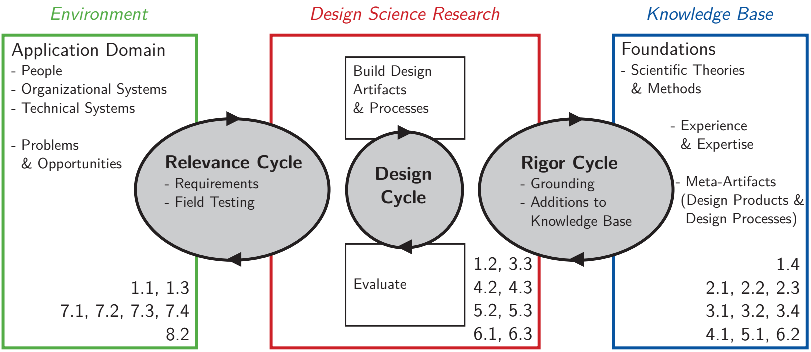

Figure 1.5: Design science research cycles identified by HEVNER et al. with mapping to sections of this thesis [HEVN10, p. 16]. Elements of the state of the art are distributed among multiple sections categorized as contribution to the knowledge base.

- The **design cycle** represents the nucleus of the research activities and is characterized by HEVNER et al. as rapidly iterating between the »construction of an artifact, its evaluation, and subsequent feedback to refine the design further [...]« [HEVN10, p. 18]. It continuously integrates contributions yielded by the rigor and relevance cycles. ADIKARI et al. additionally emphasize the prospect of creating little design artifacts [ADIK09, p. 553], allowing to decompose complex systems into a non-monolithic design.

In synopsis, the methodology of design science embraces a scientific approach to solving application-driven problems sharing many aspects also reckoned by ULRICH in an explicitly cyclic implementation. This is reflected in the structure of this thesis summarized in Figure 1.6 and incorporated section-wise into Figure 1.5.

Chapter 1 defines CaaS and its application domain, derives the subsequent research objectives and outlines the research methodology. An initial grounding to the knowledge base is carried out in Chapter 2 by reviewing the state of the art in related work. Further elements of the state of the art more specific to the individual research questions are additionally provided within the respective chapters. Chapter 3 comprises an entire design cycle dedicated to the first research question designing and validating a new method for registration of coordinate systems. The second research question is investigated in Chapter 4 analyzing IoT protocols as part of the knowledge base and designing a function-oriented model-based interface to Large-Scale Metrology instruments implemented in artifacts presented in Section 7.2. Therewith a modeling view centered around the mobile entities as physical resources of the instruments is adopted, which is maintained throughout the further design activities. A system architecture aiming at answering the third

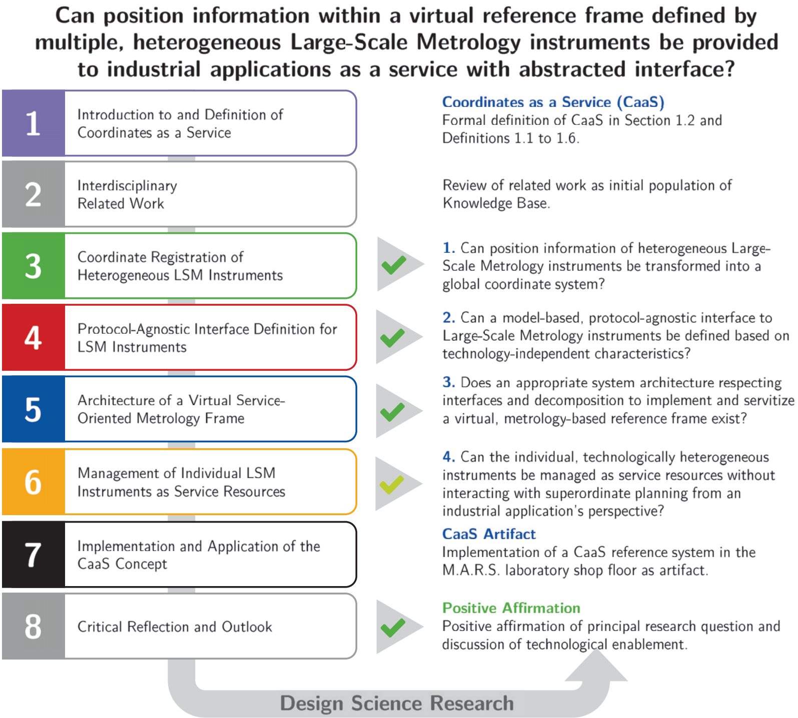

Figure 1.6: Graphical overview of the relation between research questions and thesis chapters. A linear structure is adopted in which the research guiding questions are at first treated individually in Chapters 3 - 6. On this basis, the principal research question is affirmed after the successful implementation of an artifact described in Chapter 7.

guiding question is designed in Chapter 5 after a decomposition into subsystems organized as microservices. The implementation of the according artifact is described in Sections 7.1 and 7.3. Chapter 6 describes a design cycle researching the forth guiding question. A literature review to identify characteristic properties of Large-Scale Metrology instruments in the knowledge base is leveraged to establish a capability model. Therewith effectively two modeling perspectives are adopted in Chapters 4 and 6, which address different phases of an application, namely measurement resource planning and physical measurement activity. This separation is also technically favorable, as the former is decoupled from the physical use of an instrument. The capability model is further combined with a green-field mathematical approach to resource allocation mimicking a phase space metric which is evaluated on a simulation basis. The final exposition to the application domain in form of a reference CaaS implementation and an evaluation on different applications realized as CaaS consumers is described in Chapter 7. At the same time, it describes the technical materialization of concepts developed in the previous chapter providing an additional validation. Eventually, the principal research objective, research methodology and further research potential are concluded in Chapter 8.

A further classification and structuring of the scope of the thesis is provided by outlining a heuristic framework as proposed by KUBICEK and depicted in Figure 1.7 [KUBI77]. The starting point is provided by the production scenario, which is not further specified in favour of general applicability, but which implicates the implementation of CPPS or conventional, Large-Scale Metrology tasks. Both cases take the role of a consumer when adopting the CaaS paradigm and hence enter the design of this role and its requirements.

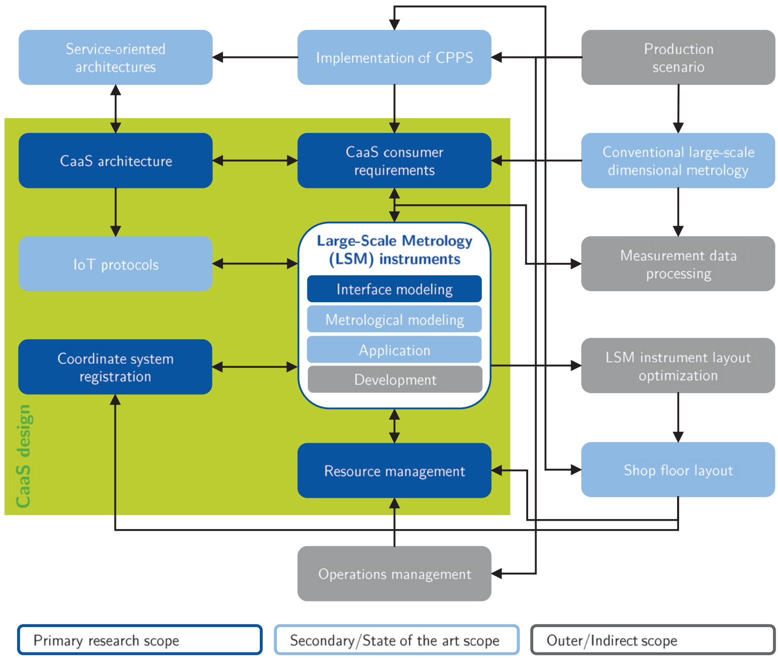

Figure 1.7: Heuristic framework of the work described in this thesis divided into three categories: Topics forming part of the technological context but lying outside the immediate scope are marked in grey. Topics marked in light blue posses a direct influence on the design of CaaS. The topics being addressed as primary scope of the research and strongly reflected in the principal research questions are highlighted in dark blue.

Moreover, the technical complexity, especially for CaaS, is a major motivation of the servitization approach, which reflects in the review of service-oriented architectures and the development of a CaaS reference architecture. In this context, IoT-protocols are reviewed to develop the model-based interfacing approach for interaction with LSM instruments within CaaS. The latter are considered as primary resources of the system, such that their application (i.e. actual physical use) and required metrological models, e.g. for uncertainty and coverage estimations, are treated at state-of-the-art level. The improvement of existing or development of novel instruments is considered out-of-scope, as is the optimization of layouts of distributed LSM instruments. The use of multiple, heterogeneous instruments creates the direct need for registering their coordinate systems as well as their management as resources. The latter is investigated as problem internal to the service and therefore considered separated form resource and operations management for the superordinate production system. These questions are immediately related to the layout of the shop floor, which is assumed to primarily be defined external to CaaS but has direct implication on the (re-)distribution of LSM instruments and hence again to coordinate registration and resource management. Lastly, any data processing after the acquisition of coordinate measurements through the service is explicitly left to the consumers of CaaS respecting their potentially arbitrary nature and separation of concerns.

2 Interdisciplinary Related Work

This chapter constitutes the first rigor cycle of the course of research by analyzing work related prima facie. It commences with an overview of the state of the art in individual Large-Scale Metrology instruments which lay the foundation of CaaS as its resources. It is followed by a review of available software and architecture in the context of the Internet of Things with the objective to identify best practices applicable to the implementation of CaaS in a sensor network perspective. The latter is complemented by a summary of major commercial software solutions in the domain of Large-Scale Metrology. Further reviews of the state of the art are carried out for coordinate registration methods in Section 3.2, IoT communication protocols in Section 4.1, digital traceability in Section 4.3 and Large-Scale Metrology instrument management in Section 6.1.

2.1 Individual Large-Scale Metrology Instruments

Large-Scale Metrology (LSM) is a domain studied since many years including multiple review articles, most notably among them the works of PUTTOCK (1978) [PUTT78], ESTLER et al. (2002) [ESTL02], PEGGS et al. (2009) [PEGG09], FRANCHESCHINI et al. (2014) [FRAN14b] as well as most recently by SCHMITT et al. (2016) [SCHM16]. Due to the increasing amount of industrial applications, research and development of Large-Scale Metrology instruments are actively emerging at the time of writing, striving for larger working volumes, lower uncertainties, shop floor robustness and lower cost. A strict definition or Large-Scale-Metrology does not exist: While PUTTOCK attributes typical linear dimensions in the range of 10 to 100 metres, SCHMITT et al. characterize it starting at a length of one metre and the typical challenges implicated by its application, e.g. high ratios of tolerances and nominal dimensions and uncontrolled measurement environments [SCHM16, p. 644]. Definition 1.3 (p. 5) is stated without dimensions, as the theoretical concepts of CaaS do not rely on a minimal working volume of the respective instruments.

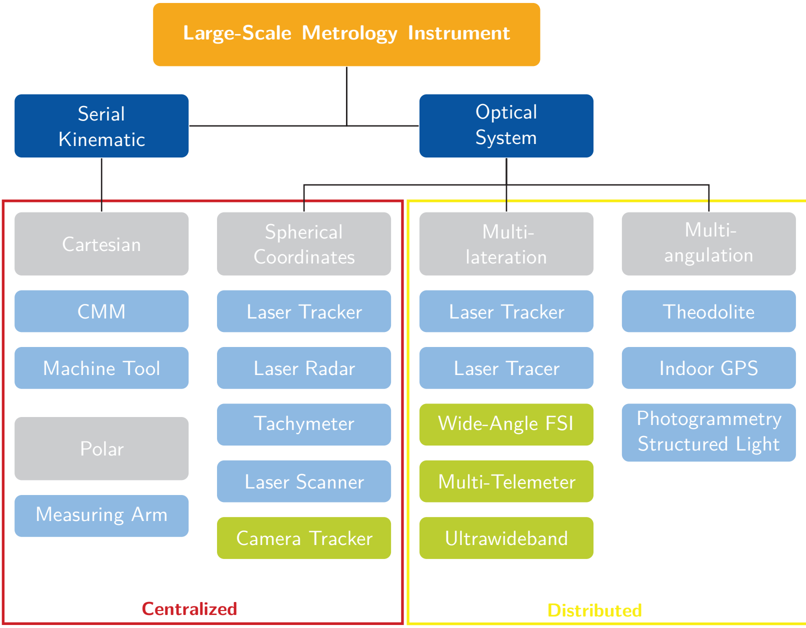

Figure 2.1: Taxonomy of Large-Scale Metrology instruments based on the version of SCHMITT et al. in 2016, which incorporates the classifications by PEGGS et al. in 2009 and ESTLER et al. in 2002. Newly added systems, which are partly still at a research stage, are colored in light green.

Figure 2.1 shows an updated taxonomy of Large-Scale Metrology instruments, which will be briefly introduced in the remainder of this Section, focussing on their distinctive characteristics rather than an in-depth description of their working principles. An arrangement along the typical relationship of working volume and uncertainty is depicted with sample illustrations in Figure 2.2. The first group is constituted by measurement systems relying on serial kinematics linking the mobile unit of the system to a reference frame, enabling the calculation of the position based on the current kinematic configuration and geometric structure. Classical Coordinate Measuring Machines (CMMs) are an instrument of this type, generally possessing a Cartesian kinematic equipped with encoders on a solid, e.g. granite frame and interacting with a workpiece by means of touch styli or scanning systems [WECK09]. They stand out by their design to maximum precision, achieving a maximum permissible error of single micrometers. As a consequence, their operation often takes place in dedicated, climatized measurement rooms. The working volume of CMMs depends on their build type and can achieve over 10 m of length. PETEREK also discusses how machine tools, unveiling kinematic similarities, can

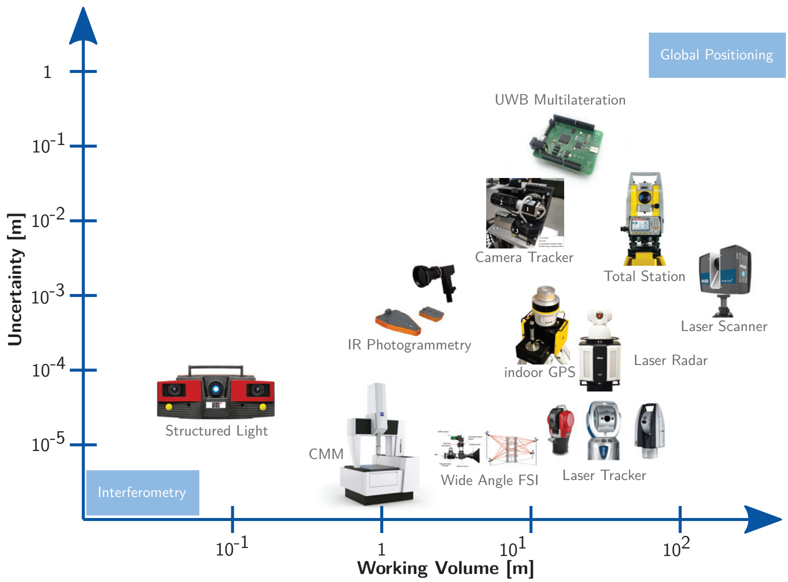

Figure 2.2: Arrangement of common Large-Scale Metrology instruments with respect to typical uncertainty contribution and working volume as illustrated cutout of the LSDM relationship diagram by FRANCHESCHINI et al. [FRAN14b, p. 1747]. Individual figures may vary depending on the configuration, e.g. also CMMs with over 10 m axis length exist, such that the categorization here has to be regarded non-exclusive.

be used for traceable measurements [PETE17]. The proximity to the shop floor and the avoidance of an additional CMM make this approach especially attractive for large components. Measuring arms are designed for portability and are, in contrast to CMMs and machine tools, not motorized but manually operated, while their polar kinematic structure is used to calculate the position from arm lengths and angular encoders.

Laser trackers are motorized portable systems measuring the position of a mobile reflecting target by actively following the latter with a laser beam used for length measurements by means of inferferometry or absolute distance measurement techniques. Together with the current readings of the beam direction from azimuth and elevation angular encoders, the target's position is synthesized in spherical coordinates. In addition, a wide range of accessories has been brought to market by the three major laser tracker manufacturers API, FARO and Leica (Hexagon MI), e.g. motorized active targets with increased acceptance angle, photogrammetry enhanced 6DoF-targets, hand-held probes and scanning units. Together with working volumes of up to approximately 100 m radius and achievable uncertainties in the order of magnitude of several ten micrometers, laser trackers have reached a high dissemination in various industrial applications [MURA16]. Alternatively, laser trackers can also be used cooperatively in a multilateration approach for coordinate measurements with reduced uncertainty [PEGG09]. The latter also is the underlying principle of the Etalon LaserTracer™, which omits the angular measurements and has an mechanical design aimed at reducing systematic errors by using an high precision mirror sphere as optical centre, allowing for length measurements with uncertainties of single micrometer magnitude [SCHW11].

Laser radar and laser scanner are systems designed to locate natural targets or featureless surfaces by combining angular encoder information with distances measured by different techniques depending on the device in question, e.g. triangulation methods, phase-shifts or time-of-flight. Apart from the omittance of specific targets, these instruments are promoted by their ability to acquire point clouds in a comparatively short time, even if per-point uncertainties are typically higher than measurements using a laser tracker. An exemplary application is the integration of the Nikon Laser Radar™ into automotive production lines [SCHÖ17].

In contrast to deducing a position from multiple lengths as in multilateration, the principle of multiangulation relies on the measurement of different angles. One of the oldest instruments of this category, originating in geodesy, is the theodolite, which in combination with distance measurements become so-called total stations or tachymeters. An industrial multilateration system is implemented with the Nikon iGPS™ system[1], which uses base transmitters at fixed reference locations emitting four rotating laser planes with known relative angles and infrared time synchronization pulses. These are received by position calculation engines (PCEs), which transmit their registration via WiFi to the system's main software to calculate the PCEs' position after applying factory calibration corrections to the laser fan geometry [NORM13, QUIN18]. Although PCEs are the natural impartible mobile units as optical receivers, the ability of simultaneous measurements favors their typical use in groups as so-called frames, measuring position and orientation at approximately 40 Hz and uncertainties of approximately 100 µm [SCHM10]. A similar measurement system is presented as »workspace Measurement and Positioning System« (wMPS) by XIONG et al. [XION12].

Advances in industrial imaging and machine vision fostered photogrammetric methods, which can roughly be grouped into three categories: Multi-camera setups determine the position of artifical or natural features through evaluating multiple perspectives with known transformations between the cameras' imaging planes. Many systems of this kind have been presented in literature or are available on the market at the time of writing [SCHM16, KORT19], including structure from motion photogrammetry techniques using consumer smartphones [MICH15,

[1] At the time of writing, the iGPS™ business line was acquired from Nikon Metrology by 7D Kinematics Inc. However, all subsequently shown experiments were carried out using a system built by Nikon Metrology, hence the preceding naming maintained.

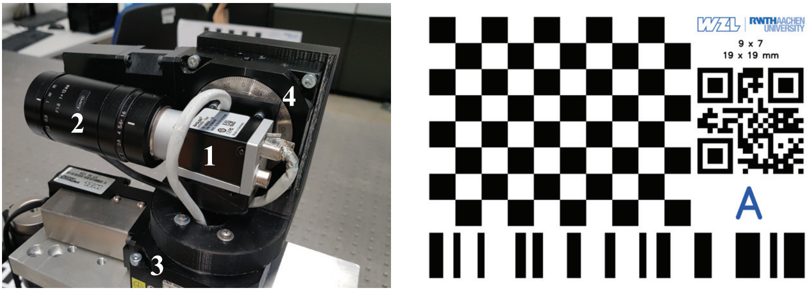

Figure 2.3: Prototype of the camera-based tracking theodolite as proposed by BODENBENNER et al. as Large-Scale Metrology instrument using printed chessboards as ultra low-cost targets and achieving an uncertainty in the order of several millimeters after calibration of camera system and kinematic [BODE20].

HERN17]. Additionally, the continual development of motion capture systems, e.g. also used in filmmaking and the gaming industry, has led to significant improvements in their metrological performance and hence their attractiveness as Large-Scale Metrology instrument [SHI20]. Another noteworthy instrument is HiBall™, which inverts the principle by localizing a mobile camera system relative to fixed markers at known locations [WELC01]. The second category comprises measurement methods based on structured light, i.e. by projecting encoded patterns onto the object respectively surface of interest and recalculating its geometry from the pattern distortion recorded in one or multiple perspectives, extensively reviewed by e.g. by GORTHI et al. [GORT10]. Examples of commercially available systems are the ZEISS COMET or gom ATOS series. In the third group, the need for multiple views is be omitted if specific targets are used which expose features with a known relative geometry. Nexonar commercially offers a system with active infrared targets and a single camera achieving uncertainties in the millimeter range [SOFT16]. BODENBENNER et al. present a prototype system depicted in Figure 2.3 combining a printed chessboard as photogrammetric target with a camera mounted on a kinematic with angular encoders similar to a laser tracker [BODE20]. Another single-camera technique for three-dimensional scene imaging is represented by time-of-flight (ToF) cameras with typical uncertainties in the centimeter range [CORT16, OPRO18].

In the field of multilateration, low-cost localization methods based on ultrawideband communication have become available. While the core principle are time-of-flight calculations, more complex algorithms are reported in literature and implemented [RIDO18, MIMO19]. With uncertainties in the order of 10 cm, typical application focus on logistics and human worker assistance. Coarse position information can also be obtained leveraging wireless radio technologies primarily intended for communication with different underlying physical principles, e.g. by means of Wi-Fi, Bluetooth or 5G using refined algorithms based on time-of-arrival calculation or signal strength evaluation[2] [BUEH18, CHEN16, ZUOZ18].

[2] Even if these systems may be not be interpreted as coordinate measuring instruments from a traditional metrologist's perspective, they relate to CaaS as no a priori performance requirements to the instruments are imposed.

On the other end, HUGHES at al. develop a multilateration system using glass spheres with a reflective index of approximately 2 which are simultaneously used as target for multiple, distributed wide-angle frequency scanning interferometry (FSI) systems [HUGH13, MART15]. FSI allows for absolute distance measurements and has for instance been applied for the alignment of the ATLAS detector at the Large Hadron Collider [COEP04]. The proposed Large-Scale Metrology instrument stands out by its built-in traceability through an integrated hydrogen cyanide absorption cell implementing the realization of the meter. Another absolute-distance multilateration method based on temporal coherence of femtosecond laser pulses is presented by LIU et al. [LIUY18].

	Base Cost	Unit Cost	Dynamic Capability	Typical Uncertainty	Working Volume	Multi-target
UWB Multilateration (Pozyx)	1 000 €	100 €	10 Hz	300 mm industrial env.	500 m extended setup	✓
Camera Tracker	5 000 € development	0.10 €	1 Hz development	5 mm	10 m	✗
Motion Capture (OptiTrack)	80 000 € 16 cameras	5 € passive	180 Hz	0.1 mm	variable >10 m	✓
Infrafred Photogrammetry (nexonar)	11 000 €	500 €	163 Hz	1 mm	3 m extendable	✓ up to 16
indoor GPS (Nikon)	300 000 €	8 000 €	25 Hz	0.1 mm	variable >10 m	✓
MSc-MS-II	under development			1 mm	–	✓ up to 4
Laser Tracker (API, Faro, Leica)	100 000 €	1 000 €	1 000 Hz	0.01 mm distance dep.	80 m configuration	✗
Wide-Angle FSI (NPL)	under development			0.01 mm	10 m configuration	✓
Large CMM	1 000 000 € configuration	–	1 Hz probing	5 µm	4 m configuration	✗

Table 2.1: Selection of Large-Scale Metrology instruments listed with properties relevant from an industrial perspective. The numbers are synthesized from respective data sheets, private communication and experience at the author's laboratory and should be treated as indication of the order of magnitude rather than exact figures.

Recovering Definition 1.3, the role of a Large-Scale Metrology instrument in CaaS is coupled to its ability to measure the position of a mobile entity. While this correspondence is directly possible for systems like laser trackers and indoor GPS, targetless systems such as structured light and laser radar must be enhanced with marker artifacts, e.g. reference spheres, contradicting the natural use of these techniques and only indirectly complying with Definition 1.3. Therefore Table 2.1 summarizes different properties of a selection of the instruments introduced above from a perspective of industrial use and direct application in a CaaS system. Their variety combined with the significant differences in cost and performance substantiate the motivation of a service-oriented integration.

2.2 Software and Architecture of Heterogeneous Sensor Networks

The integration of heterogeneous sensors and actors into a common network is regarded as part of the *Internet of Things (IoT)* concept. The latter is only vaguely defined in literature and can be interpreted to comprise every networking piece of software or hardware pushing or consuming data. SARKAR et al. identify automation, intelligence, dynamicity and zero-configuration as desirable characteristics of IoT applications, facing heterogeneity, scalability, interoperability, security and privacy as main technical challenges [SARK14]. In relation with the immense amount of participating entities, intensive research activities on all aspects of IoT have emerged over the recent years [ALFU15]. This situation is reflected in the number of available software products and commercial activities in the field, as is shown in economic reviews identifying hundreds of companies and implying the impossibility of a complete market review [LUET19].

BRECHER et al. concretize the IoT vision for the domain of production engineering within the concept of the *Internet of Production (IoP)* shown in Figure 2.4, a semantic four-layer model applicable to Cyber-Physical Production Systems [BREC17]. The first layer accommodates different types of (raw) data sources, reaching from integrated sensors over machine controllers, product respectively process information from proprietary systems to customer feedback. To incorporate the homogeneity challenge, the subsequent layer is a provisioning middleware enabling access to proprietary interfaces and different communication protocols. The analysis of the aggregated data is accommodated in the third layer, assuming the availability of ample computing power. Thereby, among others, the use of machine-learning algorithms, heuristics, complex simulations and highly available, model- and function oriented data storage is enabled. The ultimate semantic level is targeted at closing feedback loops based on the acquired and processed data. These involve both automated decisions, e.g. process reconfiguration or adaptive actor control and interaction with human operators, e.g. to objectify expert decisions.

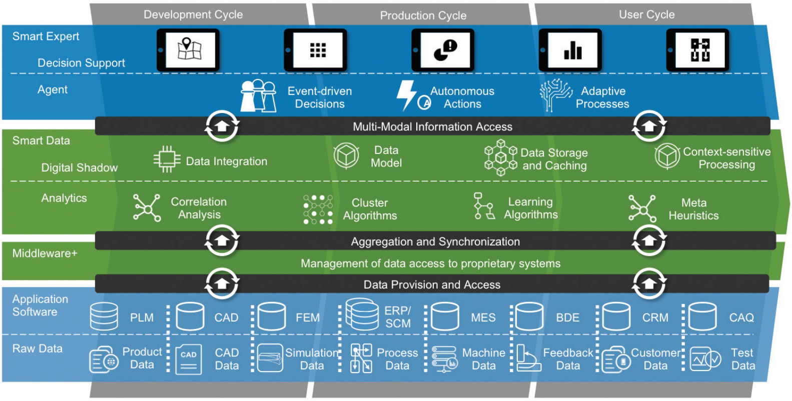

Figure 2.4: The *Internet of Production* as semantic reference model for leveraging the potential benefits of the Internet of Things for Cyber-Physical Production Systems [Brec17].

In synopsis, the *IoP* represents an abstracted perspective on the implementation of Cyber-Physical Production Systems, providing a high-level architectural design guideline for specific applications.

From a hands-on perspective of designing sensor-integrating applications to leverage the aforementioned benefits of IoT and IoP, the principal objective is to achieve an appropriately working implementation. The individual subtasks can be elucidated following Microsoft's Azure reference architecture proposal shown in Figure 2.5, incorporating a semantic similar to the IoP divided into Things, Insights and Actions [Wass19]: The data originates from sensors directly connected as IoT devices (i.e. with built-in networking capability) or is provisioned via edge devices (e.g. Bluetooth Low Energy gateways). Its ingestion into a cloud-based analytics ecosystem requires the management of participating things, the supply of a connectivity protocol[3] and networking entry point. The following path of the data can be divided along three different time scales:

- Immediate evaluations in a stream-based fashion, e.g. alerts or automated interruption of processes when predefined thresholds are exceeded.
- Short-term data aggregation with comparably short access times, denoted as warm path store, e.g. daily to weekly overviews of historic sensor data.
- Long-term data storage optimized for persistence and capacity, denoted as cold path store, e.g. sensor data aggregated over a span of several years correlatable to other stored information via appropriate metadata and ready for consumption by machine learning algorithms.

[3] The denoted IoT Hub offered by Microsoft e.g. supports MQTT and AMQP.

The action tier involves extracting added-value from the available data, i.e. the implementation of logic applications supporting the adhering business processes. Examples are prescriptive indication of the need for machine maintenance relying on model-based data analytics [DIET19] or improvement of cross-machine operational efficiency in a connected job shop [PENN19, p. 33].

From the entry point into a cloud ecosystem onwards, the implementation of virtually arbitrary applications is possible following different strategies [DUAN15]:

- Rely on existing applications as (sub-)systems which are offered under the *Software as a Service (SaaS)* paradigm, e.g. graphing tools or collaborative document editing.
- Implement custom functionality using a specific programming language respectively software environment following the *Platform as a Service (PaaS)* paradigm, e.g. hosted databases.
- Maintain an entire ecosystem with user-defined software solely relying on the hardware and networking capability of the cloud-provider, i.e. adhering to the *Infrastructure as a Service (IaaS)* paradigm.
- Compose an application system from individual components isolated in *containers*, e.g. using Docker. In literature, containerization is especially considered to support PaaS and SaaS scenarios [FUSI16].

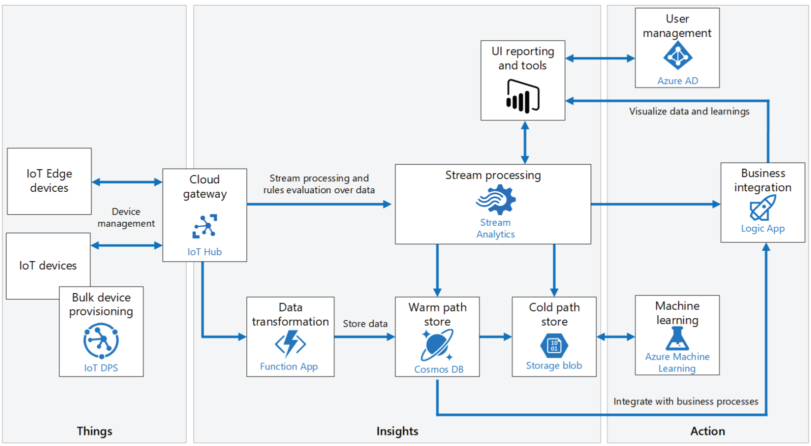

Figure 2.5: Reference architecture for applications implemented on Azure, proposed by Microsoft. The three tiers Things, Insights and Actions can be related to the Internet of Production model depicted in Figure 2.4 [WASS19].

Platforms	SaaS	PaaS	IaaS
Google Cloud, Amazon AWS, Microsoft Azure, IBM Cloud Services	●	●	●
Siemens Mindsphere, Pivotal Platform, Cloud Foundry	●	●	○
PTC ThingWorx, ThingSpeak, ADAMOS	●	○	○
GE Predix, Heroku, ScaleIT, Fraunhofer Virtual Fort Knox, SAP Cloud Platform	○	●	○
Dell Technologies Cloud, Orcale Cloud Infrastructure	○	○	●
IBM Cloud Bare Metal, Canonical MaaS, Rackspace BMaaS	○	○	○

Table 2.2: Excerpt of prominent SaaS, PaaS and IaaS providers in the field of Industrial IoT, grouped into six categories. The list has been compiled to the best knowledge of the author at the time of writing, due to the dynamicity in the field, completeness and currentness cannot be granted.

Self-evident implementations combining multiple paradigms and servitization levels are an alternative option, which is also endorsed by a variety of commercial platform providers offering SaaS, PaaS and IaaS for data processing pipelines (including storage), of which an excerpt is listed in Table 2.2.

The SaaS, PaaS and IaaS solutions hitherto discussed only weakly focus on the connection of things, i.e. distributed sensors and edge devices, to the servitization ecosystems. Effectively, two assumptions are presupposed: Connectivity of the things to a network reachable from the ecosystem and the adherence to a communication protocol with a counterpart (e.g. a messaging broker) running within the cloud. Regarding the connectivity issue AL-FUQAHA et al. report RFID, NFC, UWB, Bluetooth (Low Energy), IEEE 802.15.4, Z-Wave, WiFi and LTE-A as IoT enablers [ALFU15], while recently LoRaWAN and 5G emerged as additional technologies suited for wireless connectivity, also over long distances [EJAZ16, WIXT16]. At the same time, wired solutions, most prominently ethernet, remain a valid option. Among the communication protocols mentioned in the context of IoT, MQTT, AMQP and CoAP frequently appear, whereas in the industrial IoT domain OPC UA and MTConnect are more momentous. A detailed discussion on protocols is further elaborated in Section 4.1.

Sensing and servitization are put into a more explicit relation in the *Sensing Systems as a Service (S^2aaS)* paradigm introduced by SHENG et al., focusing on mobile phones as devices permanently connected to a cloud ecosystem, incorporating numerous sensors (e.g. accelerometers, GPS) and the ability to act as gateway for third-party sensors communicating via Bluetooth. However, description, scheduling and execution of sensing tasks, management of sensing assets as well as data storing, processing and access are identified as critical functionalities, which also recur in the IoT architectures and platforms mentioned above [SHEN13]. KANTARCI et al. extend the perspective to a massive number of generic sensing devices, additionally highlighting the question of selecting among multiple competing sensing providers [KANT15]. At the same time, incentives for providing sensing services are discussed[4], targeted at closing the gap between the cloud-centric view of a sensing service and physical sensor resources and resembling the more recent concept of data markets [OZYI18]. Regarding the architecture of S^2aaS, PERERA et al. introduce a four-layer architecture partitioned into sensors and sensor owners, sensor publishers, extended services and sensor data consumers [PERE13]. Thereby it exposes similarities to the layering scheme of the IoP and the four-layer scheme considered as one of the typical architecture models in the review by AL-FUQAHA et al. [ALFU15, p. 2349]. PERERA et al. also discuss the problem of selecting sensing services from a consumer perspective, introducing a *context-aware sensor search, selection and ranking model (CASSARAM)*. It relies on an ontology-based context property document for each sensor to span a multi-dimensional feature model which is evaluated incorporating consumer-assigned weights, enabling quantitatively supported decisions [PERE14]. The overall selection process is depicted in Figure 2.6. It should be noted that the contributions mentioned above highlight, among others, applications in the domains of smart cities, healthcare and agriculture and thereby at the same time account for scalability in systems with up to millions of contributing sensors.

Numerous further research in the domain of sensor networks is reported in literature. The *Sensor Information Network Architecture (SINA)* by SHEN et al. represents one of the early (2001) works describing the needs of a middleware for a large number of distributed sensors. It imposes hierarchical clustering and associated spreadsheets for sensors but also stands out by the introduction of a domain-specific query language (STQL) [SHEN01]. A broader review of semantic sensor specifications for web-based sensor networks has been presented by COMPTON et al., additionally reviewing different ontologies [COMP09]. IBBOTSON et al. discuss the question of a middleware for sensor networks considering request/response service consuming patterns and the event-driven nature of sensor data [IBBO10]. SCHUH et al. propose to reduce complexity by predefining sensor hardware per quantity of interest from a product perspective motivated by use-cases from the tool-making industry [SCHU14]. Decreasing hardware-variety is an approach also taken by CHI et al., suggesting a unified hardware module to gateway analog as well as as digital sensor electronics via UWB and ZigBee [CHIQ14].

The Open Geospatial Consortium (OCG) proposed the *Sensor Web Enablement (SWE)* framework, emerging from the ambition of achieving a plug-and-play system for heterogeneous sensors and gateways in geospatial sciences [MART17]. A typical data flow of applications corresponds to the scheme visualized in Figure 2.6. The sensing devices are expected to be possibly attached to resource-constrained

[4] I.e., the idea of receiving rewards in social networks for providing data from smartphone sensors is presented.

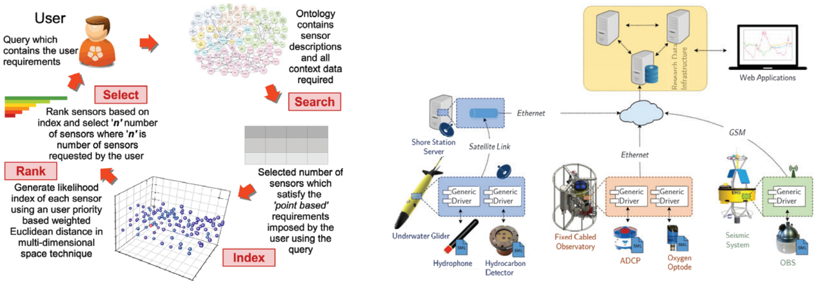

Figure 2.6: Left: Sensor selection scheme proposed by PERERA et al. starting at a user stating requirements and returning to the latter with a ranked list [PERE14]. The copyright of this figure published in 2014 belongs to IEEE. **Right:** System architecture and use-case schema of Sensor Web Enablement in Geosciences. Observation gateways with heterogeneous networking technologies enable ingestion of measurement data into a common research infrastructure. This figure by MARTINEZ et al. was reused under the CC-BY-SA 4.0 license [MART17].

observation platforms, e.g. seismic sensors on the ocean's ground with a surface buoy acting as gateway. Functionalities envisaged to address these challenges are sensor detection, identification, configuration, registration as well as simple measurement operations, data ingestion and resource constraint awareness. These are embraced in a collection of five protocols respectively standards[5], including the *Sensor Model Language (SensorML)* [OPEN14]. It understands its primary intent to »provide a robust and semantically-tied means of defining processes and processing components associated with the measurement and post-measurement transformation of observations« [OPEN14, p. ix].

SCHMITT and VOIGTMANN review the potential and importance of sensor information servitization for Cyber-Physical Production Systems as introduced in Chapter 1 [SCHM18, SCHM17]. To the best knowledge at the time of writing, this is the most recent review of its kind. A major conclusion is that with the availability of initial approaches and technologies, system integration and implementation are the most necessary work items. This perspective aligns with the approach of prioritizing a working application over an unambiguous definition of tools and IaaS, PaaS and SaaS involvement. As a consequence, the identification of separable (micro-)services within the servitization approach is crucial to achieve portability for integration with existing systems.

[5] These are OCG Puck, SensorML, SOS, O&M and EXI.

2.3 Software for using multiple Large-Scale Metrology Systems

The increasing variety in measurement instruments for dimensional metrology, intensification of quality requirements and the expansion of industrial metrology-assisted applications has led to the emerge of various software products and specialized companies. Figure 2.7 shows the dissection of a typical measurement process into five sub-steps as introduced by EMMER et al. including the according tasks and data flows [EMME18], which have also been reviewed by ZHAO et al. [ZHAO11]. Software established among end users typically covers functionality for multiple of these steps with direct internal interoperability.

The following products are well known within the community of industrial 3D metrologists[6]:

- *SpatialAnalyzer®* by New River Kinematics Inc. founded in 1994, now part of Hexagon Manufacturing Intelligence [NEWR18b].
- *PolyWorks®* by InnovMetric Inc., also founded in 1994 [INNO19].
- *Metrolog* by Metrologic founded in 1980, now part of Sandvik Machining Solutions AB [METR20].
- *Verisurf* by Verisurf Software Inc. founded in 1993 and part of Tri-Tech Precision Inc. [VERI18].
- *BuildIT* by BuildIT Software & Solutions Ltd. founded in 1990, now affiliated with Faro Technologies Inc. [BUIL18].

A detailed categorization of individual features is omitted at this stage due to the continuously increasing capabilities of the aforementioned software products. Among the latter is interfacing of different portable and Large-Scale Metrology instruments, attributable to the *Create Results* (cf. figure 2.7) step, to allow for exchangeable, cooperative and uniform interaction. Additional motivation for this feature is inferred by the requirement for simultaneous use of multiple instruments for very large volumes or in the case of occlusion, e.g. in aerospace assembly. SpatialAnalyzer® encompasses its *Unified Spatial Metrology Network (USMN)* as module targetted at such use cases, additionally including an uncertainty treatment compliant to the GUM [NEWR18a]. Related to the upcoming discussion on interfacing of Large-Scale Metrology instruments in Chapter 4, a key difference is that the software implementation to operate the respective instruments is built around their proprietary application programming interface purposed to the

[6] This list has been compiled based on experience and private conversion during the course of research and does not claim to be complete.

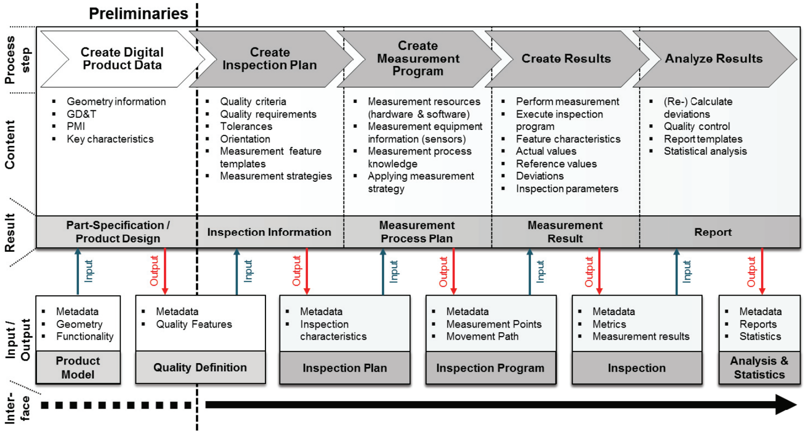

Figure 2.7: Typical process steps for dimensional metrology in quality assurance from a user's perspective as summarized by EMMER et al. [EMME18, p. 11]. This figure was reused under the CC-BY-SA 4.0 license.

integration into the main software product and focused on providing a service-oriented abstraction layer to third parties. Another modular approach to an industrial metrology software is taken by the open source project *OpenIndy* initiated in 2013, allowing users to implement their own plugins [OPEN18].

Inspection PlusPlus (I++) is a harmonization initiative originating from a loose consortium within the European automotive industry. Its intent is to decouple programming of CMMs to inspection plans from manufacturer-specific syntax. Therefore measurement instrument and programme are split into a service-oriented server-client relation with the server also encapsulating techniques necessary to achieve the claimed accuracy [GLÄS10, WENZ07, EMME18]. Another approach is constituted by the *Quality Information Framework (QiF)* ANSI standard, which aims at instantiating »[...] an integrated and holistic set of information models which, if widely adopted, can enable the effective exchange of metrology data throughout the entire manufacturing quality measurement process [...]« [ZHAO12, p. 1301]. Its hierarchial models are expressed in XML and distributed over different sections [QIF03], with *QiF Resources* being dedicated to the formal and taxonomic description of measurement instruments [QIF03, p. 388]. Figure 2.8 shows a modeling example for a laser tracker as excerpt of the standard. However, the explicit operation and interfacing of instruments lies outside the scope of QiF as its focus is on data management. Referring to Section 1.2, a QiF-based software ecosystem can embody a consumer from a servitization perspective. Comprehensive digitization of quality control and related data is also a claim of the *Kapture* software by Tecnomatix, with very little details undisclosed at the time of writing [KAPT19]. Finally, *Node-Red* as

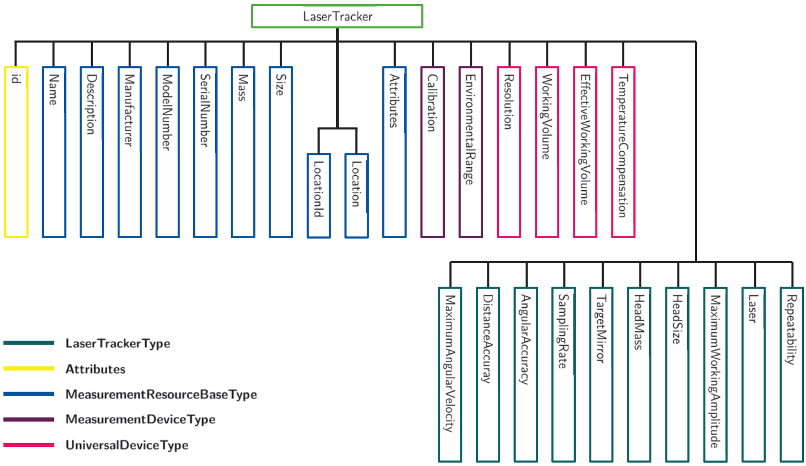

Figure 2.8: Excerpt of the QiF standard's representation of a laser tracker derived from the representation of a universal device [DIME20].

development tool for IoT applications following a visual programming paradigm oriented along data flows shall be introduced due to its increasing dissemination in academia, industry and private areas[7] [BLAC14]. It is built around the concept of nodes ingesting, diverting or processing data along paths established by connections with defined message exchange. Its implementation in JavaScript and open source license facilitate the contribution of nodes. Subsequently, compatibility to MQTT, OPC UA, Siemens MindSphere and GE Predix has been established among others [PRED19, MIND19]. Likewise, a CaaS consumer implemented in Node-Red is presented in Section 7.4.

2.4 Intermediate Summary

The industrial need for integrated Large-Scale Metrology continually increases with an application scope extending from inspection to metrology-assisted automation. Consequently, the wide range of heterogeneous Large-Scale Metrology instruments differing in principle, working volume, typical uncertainty contribution and cost has emerged. Moreover, a paradigm shift from isolated instrument use to complex Cyber-Physical Systems occurs with an immediate need for interoperability and requirement-driven, shared instrument use. In turns, these approaches require

[7]Node-Red has gained popularity for so-called smart home applications.

an abstraction from a functional perspective to decouple the position information obtained by Large-Scale coordinate measurements from the underlying technology and avoid software-induced restrictions to a metrological problem.

Moreover, the emerge of reference architectures, platforms, standardized communication protocols and servitization paradigms in the field of software engineering and industrial IoT shows both that a service-orientation is a viable integration approach to complex interconnected systems as envisaged by the Internet of Production and that a mature technological basis exists. Administration, consistent data processing and management as well as modern user interaction (e.g. based on mobile, tactile devices) in distributed systems are subjects addressed in the aforementioned domain which are expected to be beneficial for distributed, heterogeneous sensor systems.

Analyzing existing software in the domain of spatial metrology, solutions for cooperative use of Large-Scale Metrology instruments can be found, however these rely on manual registration effort and do not implement a service-oriented interface with the aim to provide a metrological reference frame to concurrent, arbitrary metrology-assisted processes, i.e. service consumers. From a perspective of manufacturing IT, they represent a monolithic architecture approach which is limited in flexibility to address the needs of modern production systems (cf. section 5.1) and their incorporation of standardized communication protocols for interoperability is limited at the time of writing.

As a result, the research objectives stated in Section 1.2 are supported by the insights of the rigor cycle in this chapter: An automatable approach to coordinate registration for cooperative or interchangeable use of Large-Scale Metrology instruments; a model-based approach to technology abstraction and communication using standardized protocols; a non-monolithic architecture design to leverage IoT platforms and concepts; and a service-oriented approach to integration respectively provenance of a virtual, metrology-based reference frame using existing instruments as resources are regarded as advances compared to the state of the art. While the engagement in CaaS as overarching concept and technical materialization is pursued as ultimate objective of the research described in this thesis, it is also expected that achievements in the context of individual research questions can provide valuable contributions.

3 Coordinate Registration of Heterogeneous LSM Instruments

Throughout this chapter, the first research question addressing the transformation of coordinates acquired by individual, heterogeneous Large-Scale Metrology instruments is investigated. Therefore, a mathematical formulation of the transformation and its adherent uncertainty is established before reviewing existing methods for coordinate registration. To mitigate identified drawbacks, a novel method is developed, simulated and successfully validated. In addition, a brief discussion on uncertainty expression is provided.

3.1 Mathematical Formulation of Coordinate Transformation and Uncertainty Propagation

If $\boldsymbol{p}_i$ is a 3D position measured in a local coordinate system Σ_i, its representation $\boldsymbol{p}_0$ in a global coordinate system Σ_0 is obtained by applying a coordinate transformation as defined by HELMERT with rotation matrix $\mathbf{R}_i$, translation vector $\boldsymbol{T}_i$ and scale factor μ_i as denoted in eq. (3.1) [WATS06]. Being a linear operation, the associated covariance $\mathbf{V}_i$ is transformed to $\mathbf{V}_0$ according to eq. (3.3)[1]. If Σ_0 and Σ_i are constituted by traceable systems, $\mu_i = 1$ is expected within uncertainties, while in other situations μ_i may reflect scale errors of a non-traceable instrument[2].

$$\boldsymbol{p}_0 = \mu_i \mathbf{R}_i \cdot \boldsymbol{p}_i + \boldsymbol{T}_i \tag{3.1}$$

$$\Leftrightarrow \boldsymbol{p}_i = \frac{1}{\mu_i} \mathbf{R}_i^T \cdot (\boldsymbol{p}_0 - \boldsymbol{T}_i) \tag{3.2}$$

[1] This procedure is coherent with Section 5.2.2 of the GUM [JGCM08] when interpreting the entries of $\mathbf{R}_i$ as sensitivity coefficients. Due to linearity, no assumptions regarding the uncertainty distributions of $\mathbf{V}_i$ are required.

[2] As a consequence, the global coordinate system used for CaaS should be defined by a traceable instrument.

Parts of the work described in this chapter have been published by the author in the following journal article:
Tilo Pfeifer, Benjamin Montavon, Martin Peterek, Ben Hughes: **Artifact-free coordinate registration of heterogeneous Large-Scale Metrology systems.** CIRP Annals, Volume 68, Issue 1, 2019.

$$\mathbf{V}_0 = \mu_i^2 \mathbf{R}_i \cdot \mathbf{V}_i \cdot \mathbf{R}_i^T \tag{3.3}$$

$$\Leftrightarrow \mathbf{V}_i = \frac{1}{\mu_i^2} \mathbf{R}_i^T \cdot \mathbf{V}_0 \cdot \mathbf{R}_i \tag{3.4}$$

Among others, a possible representation of $\mu_i \mathbf{R}_i$ is using a quaternion $\{a_i, b_i, c_i, d_i\}$ as shown in eq. (3.5), allowing unambiguous and numerically stable expression of rotations. Throughout this thesis, the seven transformation parameters are referred to as $\mathcal{P}_i$ (cf. eq. (3.6)) with covariance matrix $\mathcal{V}_i$ (cf. eq. (3.7))[3].

$$\mu_i \mathbf{R}_i := \begin{pmatrix} a_i^2 + b_i^2 - c_i^2 - d_i^2 & 2 \cdot (b_i c_i - a_i d_i) & 2 \cdot (b_i d_i + a_i c_i) \\ 2 \cdot (b_i c_i + a_i d_i) & a_i^2 - b_i^2 + c_i^2 - d_i^2 & 2 \cdot (c_i d_i - a_i b_i) \\ 2 \cdot (b_i d_i - a_i c_i) & 2 \cdot (c_i d_i + a_i b_i) & a_i^2 - b_i^2 - c_i^2 + d_i^2 \end{pmatrix} \tag{3.5}$$

$$\text{with} \quad \mu_i = \sqrt{a_i^2 + b_i^2 + c_i^2 + d_i^2} \quad \text{and} \quad a_i \geq 0$$

$$\mathcal{P}_i := \{a_i, b_i, c_i, d_i, T_{i,x}, T_{i,y}, T_{i,z}\} \tag{3.6}$$

$$\mathcal{V}_i := \mathbf{Cov}(\mathcal{P}_i) \tag{3.7}$$

When $\mathcal{P}_i$ is determined using a measurement campaign, $\mathcal{V}_i$ possesses non-zero entries originating from the instruments' individual uncertainty contributions, entering the uncertainty budget of $\boldsymbol{p}_0$ as covariance matrix S_0 as propagated in eq. (3.8). This contribution is expressed separately such that it can be excluded if the transformation effectively cancels out in further calculations.

$$\mathbf{S}_0 := \left[\frac{\partial \boldsymbol{p}_0}{\partial \mathcal{P}_i}\right] \cdot \mathcal{V}_i \cdot \left[\frac{\partial \boldsymbol{p}_0}{\partial \mathcal{P}_i}\right]^T \tag{3.8}$$

$$\mathbf{V}_0^* := \mathbf{V}_0 + \mathbf{S}_0 \tag{3.9}$$

$$v_0 = \sqrt{\text{Tr } \mathbf{V}_0} \tag{3.10}$$

$$s_0 = \sqrt{\text{Tr } \mathbf{S}_0} \tag{3.11}$$

$$v_0^* = \sqrt{\text{Tr } \mathbf{V}_0^*} = \sqrt{v_0^2 + s_0^2} \tag{3.12}$$

A combined covariance $\mathbf{V}_0^*$ can be defined as in eq. (3.9) assuming negligible correlation between $\mathbf{V}_0$ and $\mathbf{S}_0$, which is only valid if the measurement results used for coordinate system registration are statistically sufficiently independent from

[3]Without limitation, it is assumed that any other expression of coordinate transformations can be converted into the representation defined here.

the measurement results being transformed. While a full uncertainty propagation according to the GUM may be more concise, eq. (3.9) enables an estimation of $\mathbf{V}_0^*$ in situations where details of the instrument's statistical behavior are unknown or the coordinate registration procedure does not allow for analytic uncertainty propagation. The scalar uncertainty metrics v_0, s_0 and v_0^* are defined from the traces of the according covariance matrices and thereby invariant under rotations and hence for $\mu_i \approx 1$ also practically invariant with respect to coordinate system transformations[4].

3.2 Existing Methods for Transformation Parameter Estimation

The most simple case to register the coordinate systems of two instruments is if a set of $n_{locations}$ physically common points $\left\{ \boldsymbol{p}_{0,j}, \boldsymbol{p}'_{i,j} \right\}$ can be acquired such that eq. (3.13) can be minimized to obtain the required transformation parameters.

$$\min_{\mathcal{P}_i} \sum_{j=1}^{n_{locations}} \left|\left| \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j} \right|\right| = \min_{\mathcal{P}_i} \sum_{j=1}^{n_{locations}} \left|\left| \boldsymbol{p}'_{0,j} - \mu_i \mathbf{R}_i \cdot \boldsymbol{p}_{i,j} - \boldsymbol{T}_i \right|\right| \tag{3.13}$$

Apart from numerical minimization with arbitrary methods, EGGERT et al. present four different algorithms to solve the least-squares problem, e.g. leveraging a matrix formulation [EGGE97]. If the mobile entities of the Large-Scale Metrology instruments are mutually incompatible, another possibility to acquire the set of common points is by probing, either using dedicated probing entities or targets of known dimension (e.g. SMRs). The mathematical problem remains as stated in eq. (3.13), although in addition to the uncertainty of the position measurements themselves, the uncertainty contributions of the contact process and, if applicable, probing entity must be taken into account.

Alternatively, the use of calibrated artifacts interfacing mobile entities of multiple instruments is an approach to overcome the aforementioned limitation. Mathematically, eq. (3.13) is extended with geometric constraints $\mathbf{O}_j \cdot \boldsymbol{u}_k$ to eq. (3.14).

$$\min_{\mathcal{P}_i, \mathbf{O}_{1 \ldots n_{locations}}} \sum_{j=1}^{n_{locations}} \sum_{k=1}^{n_{constraints}} \left|\left| \boldsymbol{p}_{0,j,k} - \mu_i \mathbf{R}_i \cdot \boldsymbol{p}'_{i,j,k} - \boldsymbol{T}_i - \mathbf{O}_j \cdot \boldsymbol{u}_k \right|\right| \tag{3.14}$$

Herein $\boldsymbol{u}_k$ represents the calibrated offset between two targets, which is denoted with variable index to account for artifacts with more than one entity per instru-

[4] These quantities are useful when a scalar metric is needed, e.g. in residual plots, comparisons with data sheets or rough estimates of uncertainty budgets.

ment. Depending on the explicit methods, the orientation $\mathbf{O}_j$ of the artifact may be unknown and part of the minimization problem. The thereby inferred sensitivity poses, compared to the previously mentioned methods, a contribution to the uncertainty budget, as does the remaining uncertainty of the artifact's calibration. Consequently, this methods can also be used with probing systems.

The need for calibrated artifacts can be omitted if both instruments can be used to measure identical geometrical features, e.g. spheres, rings, planes or lines. The mathematical evaluation can either be carried out following eq. (3.13) using the determined feature locations or taking into account the geometry of the features. An in-depth discussion of applicable methods to align measurement data to nominal geometries is carried out by WECKENMANN et al. [WECK09].

Regarding the uncertainty budget, additional contributions occur from the feature calculation method (e.g. circle fitting) and feature consistency[5]. The registration of point clouds can be classified as similar method and is of major interest when using optical probing respectively surface scanning systems. The mathematical difficulty lies in the alignment of the point clouds representing the same surface but at different locations. It is solved by the *Iterative Closest Point Algorithm (ICP)* implemented in multiple variants. Likewise, its uncertainty budget must account for both the surface variation and the uncertainty associated with the (optical) measurement principle, which is often complex to estimate as further discussed by LEACH [LEAC19].

In addition to hitherto presented methods, hybrid approaches accompanied by an appropriate mathematical model are also possible to determine the coordinate registration parameters. Figure 3.1 summarizes different uncertainty contributions that may be expected based on the specific approach chosen. A potentially interesting device for such methods is constituted by the modular probe presented by MAISANO et al. [MAIS18]. Moreover, a more rigorous treatment of measurement uncertainty is possible by using weighted versions of the according methods and relating equations for minimization. ZHAO et al. developed a modified version of the common points approach incorporating local geometric constraints derived from the instruments' uncertainty models [ZHAO18]. Ultimately, CaaS does not prescribe a certain coordinate registration method to determine $\mathcal{P}_i$ and $\mathcal{V}_i$, such that the flexibility to use any method, among others the ones mentioned in this section, is preserved.

[5] The physical regularity, e.g. plane flatness, may have a significant influence and lead to different features effectively measured

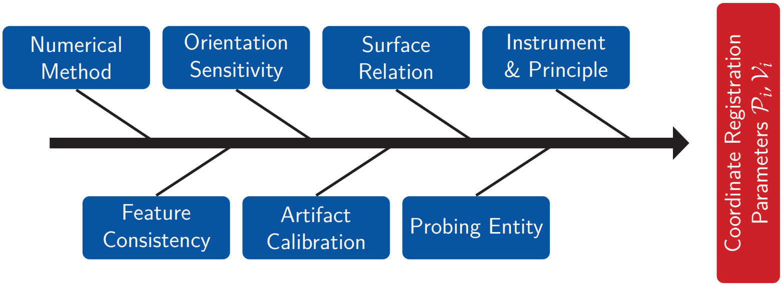

Figure 3.1: Different influences that may contribute to the uncertainty budget of the coordinate registration parameters depending on the methods respectively algorithms used. Typical contributions such as operator and environment are omitted as they apply to all methods.

3.3 Novel Method for Artifact-Free Registration of Heterogeneous Large-Scale Metrology Instruments

To enable systematic integration of arbitrary Large-Scale Metrology instruments into an existing CaaS environment with high potential for automation, a coordinate system registration method with the following properties would be beneficial:

- No calibrated artifacts with target-specific interfaces are required.
- The procedure does not involve tactile or optical probing of common points or features.
- Full propagation of measurement uncertainties to the obtained transformation parameters is enabled.
- The involved measurement campaign can be adapted to local constraints.
- The method is applicable to arbitrary Large-Scale Metrology instruments with heterogeneous and mutually incompatible targets.

No state-of-the-art registration method described in the previous section simultaneously maintains aforementioned benefits. Therefore a novel method for artifact-free registration of heterogeneous Large-Scale Metrology instruments was developed as part of a design cycle throughout the course of research.

3.3.1 Method Description and Mathematical Modeling

The method is described and modeled assuming two correctly functioning and calibrated instruments[6] $\mathcal{M}_0$ and $\mathcal{M}_i$, of which $\mathcal{M}_0$ defines the target coordinate

[6] Hereby it is explicitly assumed that the position information provided is corrected for all known systematic errors such that their contribution to the uncertainty budget is significantly smaller

system Σ_0[7]. Figure 3.2 depicts the core measurement setup used: The targets of both instruments $\mathcal{M}_0$ and $\mathcal{M}_i$ are attached to an arbitrary rigid body[8] with constant distance l, further more descriptively referred to as rigid bar. For $j = 1, \ldots, n_{locations}$ different stable locations (including reorientation) of the bar within the jointly covered working volume $\mathcal{W}$, the position information $\boldsymbol{p}'_{0,j}$, $\mathbf{V}'_{0,j}$ and $\boldsymbol{p}_{i,j}$, $\mathbf{V}_{i,j}$ is captured. Expressed in Σ_0 using eq. (3.1), for each location the positions of both targets measured are separated by a vector $\boldsymbol{u}_j$ of length l.

$$\boldsymbol{p}'_{0,j} = \boldsymbol{p}_{0,j} + \boldsymbol{u}_j = \mu_i \mathbf{R}_i \cdot \boldsymbol{p}_{i,j} + \boldsymbol{T}_i + \boldsymbol{u}_j \tag{3.15}$$

Following eq. (3.15), a residual r_j can be defined as in eq. (3.16). After rewriting the vector norm in scalar products in eq. (3.17), the small angle approximation is applied to obtain eq. (3.19)[9].

$$\begin{aligned}
r_j^2 &= \left|\left|\boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j} - \boldsymbol{u}_j\right|\right|^2 && (3.16)\\
&= \left\langle \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j} - \boldsymbol{u}_j, \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j} - \boldsymbol{u}_j \right\rangle && (3.17)\\
&= \left\langle \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j}, \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j} \right\rangle - 2 \cdot \left\langle \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j}, \boldsymbol{u}_j \right\rangle + \left\langle \boldsymbol{u}_j, \boldsymbol{u}_j \right\rangle && (3.18)\\
&= \left|\left|\boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j}\right|\right|^2 - 2 \cdot \left|\left|\boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j}\right|\right| \cdot \left|\left|\boldsymbol{u}_j\right|\right| \cdot \underbrace{\cos \sphericalangle_j}_{\approx 1} + \underbrace{\left|\left|\boldsymbol{u}_j\right|\right|}_{l}^2 && (3.19)\\
&\approx \left(\left|\left|\boldsymbol{p}'_{0,j} - \mu_i \mathbf{R}_i \cdot \boldsymbol{p}_{i,j} - \boldsymbol{T}_i\right|\right| - l\right)^2 && (3.20)
\end{aligned}$$

Therewith the number of unknown parameters is effectively reduced to 8, i.e. $\mathcal{P}_i$ and l as distance between the measurement points of both targets. The parameters are estimated by minimizing a χ^2-sum in eq. (3.23) over the residuals r_j^2 at $n_{locations}$ bar locations. Assuming uncorrelated covariance matrices of the individual measurements in eq. (3.21), the weights σ_j^2 are defined in eq. (3.22) by exploiting the linear transformation property of covariance matrices to effectively project $\mathbf{V}_j$ along the direction of $\boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j}$ through multiplication with the corresponding unit vector [ZHAN17, p. 291].

than the statistical contributions.

[7] In a CaaS setup, $\mathcal{M}_0$ either defines the global coordinate system or has a known transformation to the latter.

[8] The applicability of any body sufficiently rigid during the measurement campaign motivates the declaration as *artifact-free*.

[9] The approximation is expected to be valid close to the optimal solution. The impact on the convergence of the minimization is investigated in the subsequent simulations.

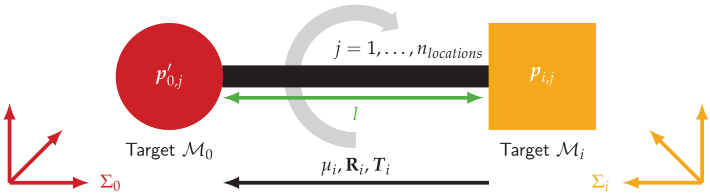

Figure 3.2: Sketch of the mobile part of the measurement setup: Both entities of $\mathcal{M}_0$ and $\mathcal{M}_i$ are fixed to a rigid body in arbitrary distance l.

$$\mathbf{V}_j = \mathbf{V}'_{0,j} + \mathbf{V}_{0,j} = \mathbf{V}'_{0,j} + \mu_i^2 \mathbf{R}_i \cdot \mathbf{V}_{i,j} \cdot \mathbf{R}_i^T \tag{3.21}$$

$$\sigma_j^2 = \frac{\left\langle \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j}, \mathbf{V}_j \cdot \left(\boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j} \right) \right\rangle}{\left|\left| \boldsymbol{p}'_{0,j} - \boldsymbol{p}_{0,j} \right|\right|^2} \tag{3.22}$$

$$\chi^2 = \sum_{j=1}^{n_{locations}} \frac{r_j^2 \left(\boldsymbol{p}'_{0,j}, \boldsymbol{p}_{i,j}, \mathcal{P}_i, l \right)}{\sigma_j^2 \left(\boldsymbol{p}'_{0,j}, \boldsymbol{p}_{i,j}, \mathbf{V}'_{0,j}, \mathbf{V}_{i,j}, \mathcal{P}_i \right)} \tag{3.23}$$

Eq. (3.24) represents a nonlinear minimization problem, which can be solved using iterative techniques[10]. For correctly defined weights representing statistical error contributions, the covariance of the obtained parameters is estimated by the inverse Hessian matrix of χ^2 as denoted in eq. (3.25).

$$\mathcal{P}_i^{\text{opt}} = \min_{\mathcal{P}_i, l} \chi^2 \tag{3.24}$$

$$\mathcal{V}_i^{\text{opt}} = \left[\left. \frac{\partial^2 \chi^2}{\partial \mathcal{P}_i^2} \right|_{\mathcal{P}_i^{\text{opt}}, l^{\text{opt}}} \right]^{-1} \tag{3.25}$$

3.3.2 Monte Carlo Simulation

To verify the chosen approach for uncertainty propagation, a Monte Carlo simulation of the proposed method was implemented, simultaneously inspecting the convergence under the small angle approximation in eq. (3.19). For a given set of transformation parameters $\mathcal{P}_i^*$, a set of randomly distributed reference positions $\boldsymbol{p}'^*_{0,j}$ for $\mathcal{M}_0$ within a volume $\mathcal{W}^*$ is generated. The ideal measurements of $\mathcal{M}_i$ are generated in Σ_0 by individually adding a uniform randomly oriented vector of

[10] Throughout the work presented here, MINUIT was used as a minimizer [JAME75].

length l^* to $\boldsymbol{p}'^*_{0,j}$ and applying the inverse transformation to Σ_i defined by $\mathcal{P}_i^*$ to obtain $\boldsymbol{p}^*_{i,j}$. Within a Monte Carlo data set, statistical contributions $\boldsymbol{\varepsilon}'_{0,j,k}$ and $\boldsymbol{\varepsilon}_{i,j,k}$ drawn from zero-centered normal distributions with covariances $\mathbf{V}'_{0,j} = \mathbf{1}\bar{\sigma}_0$ and $\mathbf{V}_{i,j} = \mathbf{1}\bar{\sigma}_i$ are added to $\boldsymbol{p}'^*_{0,j}$ and $\boldsymbol{p}^*_{i,j}$ for $k = 1, \ldots, n_{samples}$. For each sample, the minimization defined in eqs. (3.6) and (3.25) is conducted, resulting in a distribution of parameters $\mathcal{P}^{\text{opt}}_{i,k}, \mathcal{V}^{\text{opt}}_{i,k}$.

Figure 3.3 shows the parameter distribution for a virtual setup where Σ_0 and Σ_i are shifted by $\boldsymbol{T}_i^* = (-7.0, 4.0, 2.0)$ m and rotated by $\alpha_z = 73.1°, \alpha_y = 4°$ and $\alpha_x = -2°$ in ZYX/Yaw-Pitch-Roll Euler convention, corresponding to a setup with roughly aligned z-axes and a quaternion of $a_i^* = 0.802, b_i^* = 0.035, c_i^* = 0.018, d_i^* = 0.596$. The Monte Carlo sample consists of $n_{samples} = 10\,000$ data sets with $\bar{\sigma}_0 = 20\,\mu\text{m}$ and $\bar{\sigma}_i = 500\,\mu\text{m}$ for a measurement campaign with $n_{locations} = 65$ locations within a volume of $\mathcal{W}^* = 10\,\text{m} \times 10\,\text{m} \times 5\,\text{m}$. The simulation results are analyzed with respect to the following criteria:

(1) The fraction of converged samples $n_{converged}/n_{samples}$.

(2) The agreement of $\mathcal{P}^{\text{opt}}_{i,k}$ and its sample mean with $\mathcal{P}_i^*$.

(3) The agreement of $\mathcal{V}^{\text{opt}}_{i,k}$ and its sample mean with the sample covariance over $\mathcal{P}^{\text{opt}}_{i,k}$.

(4) The magnitude of the individual entries' standard deviation over $\mathcal{V}^{\text{opt}}_{i,k}$.

The histograms plotted in Figure 3.3 show positive agreement for criteria (2) and (3) and are exemplary for all carried out simulation runs. Among these, a convergence fraction of over 99.7% for criterion (1) and standard deviations two orders of magnitude smaller than the respective sample mean for criterion (4) were observed. Moreover, the distribution of χ^2 over the number of degrees of freedom (NDF)[11] follows the ideal χ^2-distribution, hence the weight definition in eq. (3.22) is regarded as appropriate.

Throughout the simulation sequences, the influence of the l, $\mathcal{W}^*$ and $n_{locations}$ on $\mathcal{V}^{\text{opt}}_{i,k}$ was analyzed for constant $\bar{\sigma}_0$ and $\bar{\sigma}_i$, unveiling that the components of $\mathcal{V}^{\text{opt}}_{i,k}$ decrease with $1/\sqrt{n_{locations}}$ as expected for χ^2-sums, while variations of l show now systematic influence. Increasing $\mathcal{W}^*$ reduces the resulting parameter covariance for a_i, b_i, c_i and d_i as shown in Figure 3.4, however, for Large-Scale Metrology instruments $\mathbf{V}'_{0,j}$ and $\mathbf{V}_{i,j}$ often increase with $\left|\left|\boldsymbol{p}'_{0,j}\right|\right|$ respectively $\left|\left|\boldsymbol{p}_{i,j}\right|\right|$. Including uncertainty models for $\mathcal{M}_0$ and $\mathcal{M}_i$, the design of an uncertainty-optimized measurement campaign becomes an optimization problem of its own, which can be handled partially reusing the developed Monte Carlo simulation.

[11] The number of degrees of freedom is $n_{locations} - 8$, i. e. the number of locations subtracted by the number of free minimization parameters.

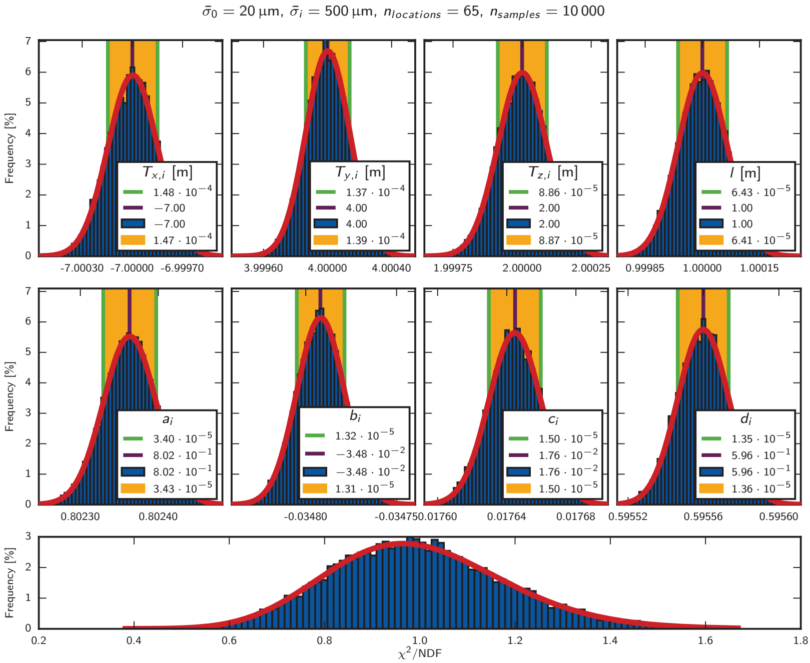

Figure 3.3: Distribution of $\mathcal{P}_{i,k}^{\text{opt}}$ within one Monte Carlo data set overlaid with ideal probability density functions (red). The standard deviation (orange) and mean (blue) estimated by sample variance agree with the set values $\mathcal{P}_i^*$ (purple) and the mean over covariance estimates (green),i.e. criteria (2) and (3) apply.

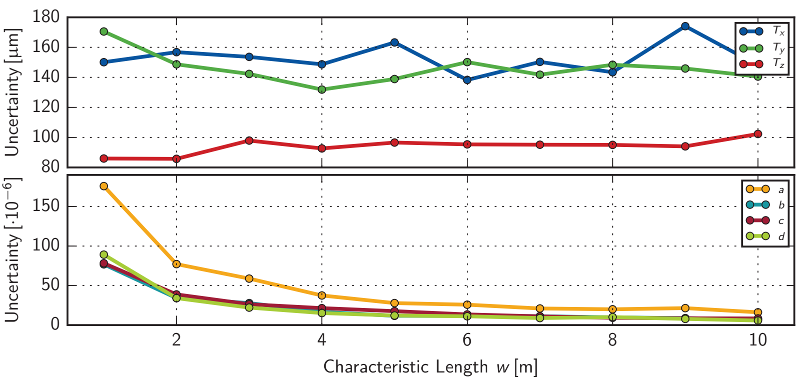

Figure 3.4: Obtained standard deviation for the parameters of $\mathcal{V}_{i,j}^{\text{opt}}$ when varying $\mathcal{W}^*$ as $2w \times 2w \times w$ within the simulation scenario analyzed in Figure 3.3. The observed variations within $T_{x,y,z}$ are expected to be a result of the different strategies at same $n_{locations}$, while the uncertainty of the quaternion part clearly decreases. The light blue curve of b is nearly invisible due to its similarity to the curve of c.

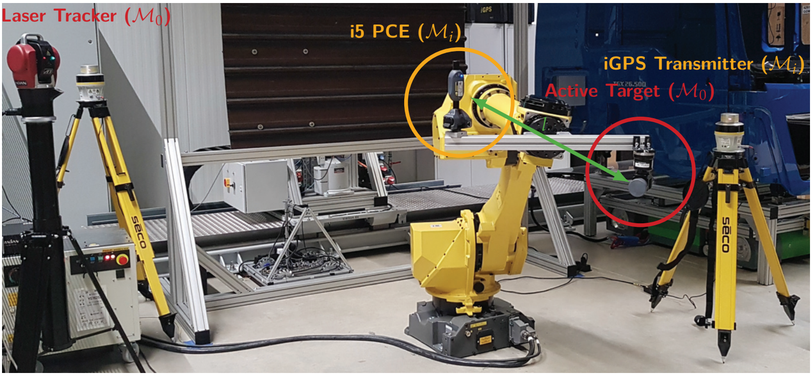

Figure 3.5: Setup to register the coordinate systems of Nikon iGPS™ ($\mathcal{M}_i$, orange, two of six transmitters visible) and API Radian™ ($\mathcal{M}_0$, red, mounted on tripod on the left side) according to Figure 3.2. The robot is used as a pure mover to obtain different orientations and locations of the bar.

3.3.3 Experimental Validation

The developed procedure is validated in two experiments: At first, the general applicability and potential for automation are evaluated registering the coordinate systems of a Nikon iGPS™ and an API Radian™ laser tracker using a robot as mover. Thereafter, two API Radian™ laser trackers are registered and the deviation at different locations of a jointly used SMR is analyzed. Figure 3.5 shows the setup for the first case, where the API Radian™ in conjunction with an active target represents instrument $\mathcal{M}_0$ and a Nikon iGPS™ setup with six transmitters in box layout and a mobile i5 PCE unit constitutes $\mathcal{M}_i$.

Both targets are fixed to an aluminum bar attached as the robot's end effector, replicating a potential industrial scenario. The instruments were calibrated prior to the experiments using their proprietary calibration routines. Measurement strategies were randomly generated with different $n_{locations}$ and $\mathcal{W}^*$ (Table 3.1). For the laser tracker at each stable location 1 000 data points were captured in spherical coordinates and $\boldsymbol{p}'_{0,j}$, $\mathbf{V}'_{0,j}$ estimated by sample variance[12]. For the indoor GPS system, 100 data points were recorded per location and $\boldsymbol{p}_{i,j}$, $\mathbf{V}_{i,j}$ estimated by sample covariance in Cartesian coordinates.

[12]It is assumed that the spherical coordinates are directly related to the laser tracker's encoders and distance measurement, such that they are uncorrelated if the contribution from the target is negligible.

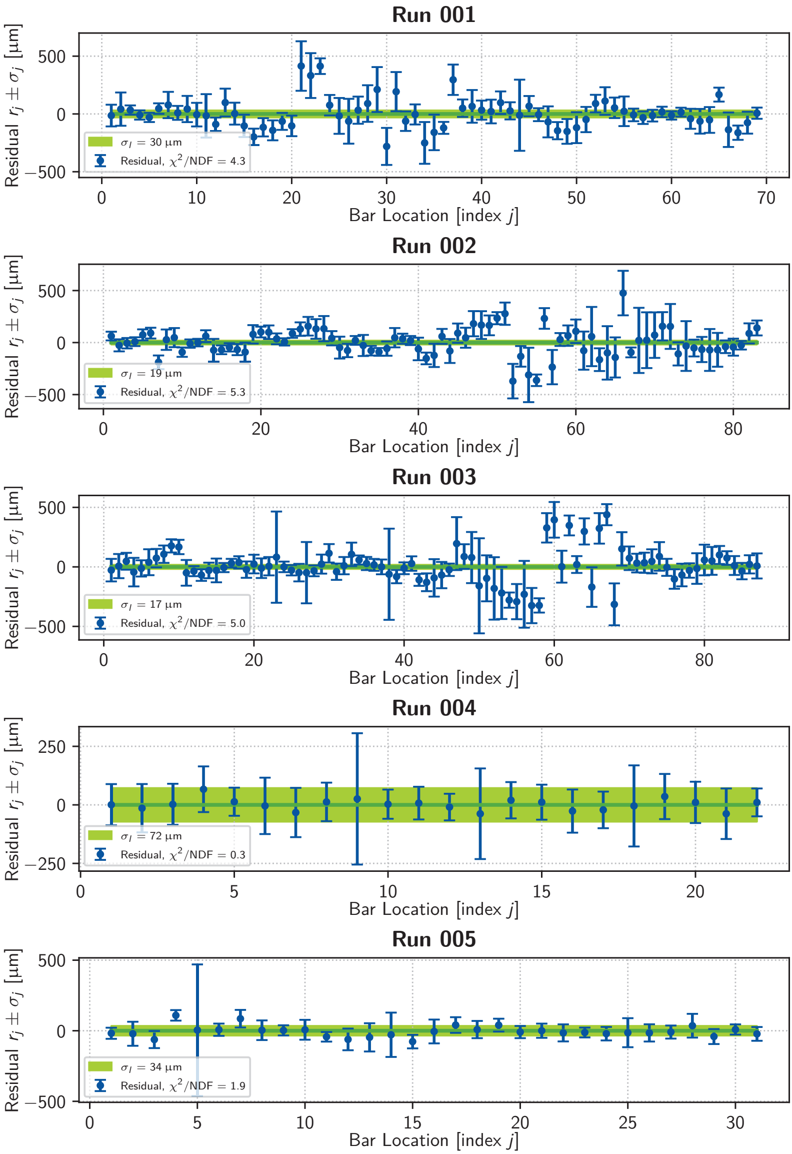

Figure 3.6: Residuals of the five measurement runs for a coordinate registration between Nikon iGPS™ and API Radian™ with results denoted in Table 3.1. The light green area corresponds to the estimated parameter uncertainty of l, while r_j and σ_j are computed according to eqs. (3.16) and (3.22) for the obtained parameters and plotted with error bars.

$\mathcal{P}_i$	Run 001	Run 002	Run 003	Run 004	Run 005
a_i	0.596238 $\pm$ 0.000026	0.595946 $\pm$ 0.000012	0.596044 $\pm$ 0.000012	0.597361 $\pm$ 0.000020	0.595481 $\pm$ 0.000044
b_i	0.000168 $\pm$ 0.000013	0.000140 $\pm$ 0.000011	0.000175 $\pm$ 0.000012	$-$ 0.002767 $\pm$ 0.000022	0.000676 $\pm$ 0.000069
c_i	0.005527 $\pm$ 0.000017	0.005511 $\pm$ 0.000011	0.005435 $\pm$ 0.000008	0.002672 $\pm$ 0.000029	0.005333 $\pm$ 0.000022
d_i	0.803041 $\pm$ 0.000024	0.802828 $\pm$ 0.000012	0.802815 $\pm$ 0.000015	0.802165 $\pm$ 0.000015	0.802830 $\pm$ 0.000017
$T_{x,i}$ [m]	3.829928 $\pm$ 0.000317	3.826884 $\pm$ 0.000134	3.827486 $\pm$ 0.000187	3.852264 $\pm$ 0.000212	3.823449 $\pm$ 0.000167
$T_{y,i}$ [m]	3.013446 $\pm$ 0.000076	3.013652 $\pm$ 0.000074	3.013358 $\pm$ 0.000057	3.004823 $\pm$ 0.000118	3.015186 $\pm$ 0.000092
$T_{z,i}$ [m]	$-$ 1.604376 $\pm$ 0.000184	$-$ 1.603318 $\pm$ 0.000072	$-$ 1.602821 $\pm$ 0.000084	$-$ 1.571914 $\pm$ 0.000224	$-$ 1.601905 $\pm$ 0.000287
l [m]	0.562413 $\pm$ 0.000030	0.561860 $\pm$ 0.000019	0.562137 $\pm$ 0.000017	0.562591 $\pm$ 0.000072	0.561992 $\pm$ 0.000034
$\mathcal{W}^*$ [m]	2.68, 1.94, 1.99	2.87, 1.93, 2.13	3.18, 2.37, 1.76	0.40, 0.60, 0.33	0.57, 0.73, 1.34
$n_{locations}$	69	83	87	22	31
χ^2/NDF	4.34	5.31	4.96	0.30	1.91

Table 3.1: Overview of $\mathcal{P}_i^{\text{opt}}$ and campaign characteristics for an exemplary measurement series. The uncertainties provided are the square roots of diagonal elements of $\mathcal{V}_i^{\text{opt}}$. The quaternions represent a rotation mostly around the z-axis (normal to the shop floor).

Table 3.1 lists consistent results for a coherent series of measurements, while convergence was achieved for all experiments conducted. The modeled behavior of $\mathcal{V}_i^{\text{opt}}$ depending on $n_{locations}$ and $\mathcal{W}^*$ is confirmed. Comparing the residuals displayed in Figure 3.6, the observed clustering suggests that the use of a smaller volume occludes systematic effects. This hypothesis is supported by values above 1 for χ^2/NDF, indicating underestimated statistical uncertainties or unmodeled systematic effects. According to eq. (3.25), high values of χ^2 lead to smaller estimates for $\mathcal{V}_i^{\text{opt}}$, explaining why the individual results for $\mathcal{P}_i^{\text{opt}}$ do not completely agree within uncertainties. Possible systematic effects are changes in transmitter visibility for the indoor GPS or unconsidered effects within the active target of the laser tracker. Moreover, the uncertainty estimates $v_{i,j} = \text{Tr}\,\mathbf{V}_{i,j}$ of approximately 50 µm are lower than typical values of 100 µm (coverage factor 1) reported in literature [QUIN18, pp. 46-55]. With $v_{0,j} \gg v'_{0,j}$, the uncertainty estimate of the indoor

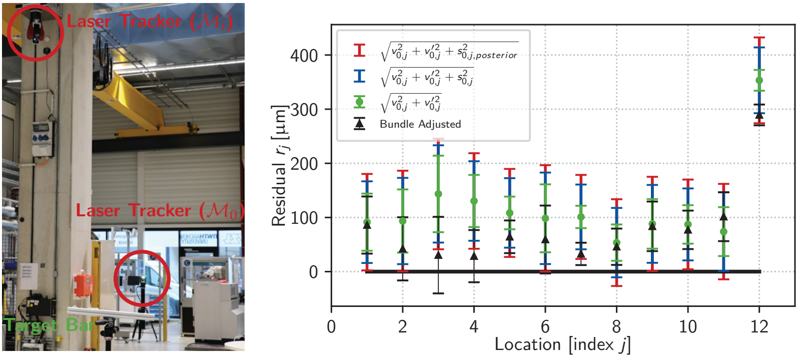

Figure 3.7: Left: Two API Radian$^{\text{TM}}$ laser trackers positioned within the shop floor's volume for which the novel coordinate system registration method was evaluated. **Right:** Deviation between common SMR locations measured by both laser trackers after being transformed to Σ_0. The distribution of residuals is one-sided due to the non-negative nature of the euclidean norm. Red error bars represent the total uncertainty after a correction of the transformation parameters' contribution by means of posterior weighting [FORB12]. For reference, the results using a traditional bundle adjustment are shown. Figure A.2 in the Appendix contains details of the residuals.

GPS system poses the major contribution to the weight factors of the χ^2-sum, hence changing its uncertainty model significantly affects $\mathcal{V}_i^{\text{opt}}$[13].

To further validate the proposed method, it was applied to register the coordinate systems of two API Radian™ laser trackers at their typical position on the shop floor, using an aluminum bar with two standard SMRs. The obtained parameters were used to transform the position information of a single SMR measured by both laser trackers into the coordinate system of the first instrument. Figure 3.7 displays the measurement setup and distribution of residuals. The latter sustain a physically correct alignment of the coordinate systems. The larger deviations in direct comparison with a transformation based on a bundle adjustment approach are expected, as the latter procedure is directly evaluated on the common SMR locations and does not comprise a degree of freedom in l. Appendix A shows the results of a repetition of this experiment for a larger set of common locations (Figure A.3), their spatial distribution (Figures A.4 & A.5) as well as the obtained transformation parameters (Table A.2).

[13] Whether to modify the uncertainty model to occlude systematic effects within the statistical uncertainties or opt for a separate treatment is a decision to be taken by the individual user.

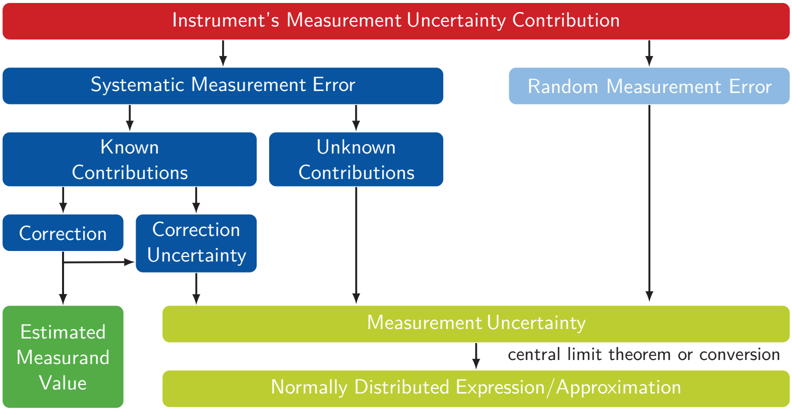

Figure 3.8: Correction of systematic measurement error contributions and expression of measurement uncertainty according to the GUM [JGCM08]. Its normal distributed expression is chosen as universal representation within CaaS. This figure is an extended version of a schematic by OHLENFORST [OHLE19, p. 23].

3.4 Comment on Uncertainty Expression

Although the transformation into a different coordinate system stated in eq. (3.7) does not imply any requirements to the expression of uncertainty in terms of distribution and coverage factor, only a consistent expression enables the interchangeable and cooperative use of Large-Scale Metrology instruments in applications and control loops where knowledge on the uncertainty is critical. Compatible to the GUM, an expression of uncertainty as unexpanded covariance matrix of a multivariate normal distribution is endorsed.

Thereby it is presupposed that the measurement results of the individual instruments have been corrected for systematic errors and the remaining uncertainty of their correction enters the uncertainty budget as summarized in Figure 3.8. The choice of a normal distribution is motivated by several reasons: Predominantly, Large-Scale Metrology instruments are typically complex systems fusing information of multiple sensor sources as well as involving different calibrations and compensation. Therefore the central limit theorem according to Annex 5 of the GUM can be assumed if there are no dominating contributions [JGCM08, pp. 70-78]. Furthermore, variance conversion factors for other types of distributions, can be calculated as denoted in the GUM's *Type B evaluation of standard uncertainty* [JGCM08, pp. 11-14]. While examples for uniform and triangular distributions are included in the latter, the general calculation follows the standard integrals for obtaining mean value and variance for continuous probability density functions.

It is assumed that the use of Large-Scale Metrology instruments within CaaS does not occur at any system boundaries leading to one-sided stochastic distributions. Eventually, a representation of uncertainties related to normal distributions facilitates the adherence to the GUM for propagation of uncertainty both within a CaaS system as well as in subsequent processing steps.

The chosen approach favors applicability with reduced complexity over the greatest possible detail on the statistical nature of the uncertainty contributions associated with the measurements. Due to the modularity on various levels of the CaaS concept, this choice can be altered if Definition 1.1 is modified to contain information on the statistical distribution and the interfaces defined in Chapters 4 and 6 are adapted.

3.5 Intermediate Summary

A suitable representation for the transformation of position information from a local to a global coordinate system using a quaternion-based Helmert transformation and including expression of uncertainties contributed by the instrument as well as the transformation among coordinate systems has been established. While for the integration of Large-Scale Metrology instruments as CaaS resource any method determining the required transformation parameters and their uncertainty can be used, different drawbacks of existing methods have been identified. Therefore a novel, artifact-free method allowing coordinate registration for arbitrary coordinate measuring systems with overlapping working volumes and high potential for automation has been conceptualized, simulated and successfully validated in different experiments. To allow for different registration methods such that the most appropriate approach can be chosen according to the used instruments, targets and boundary conditions, the further design of CaaS does not imply the use of a specific registration method, but rather the unified representation as introduced in Section 3.1. Regarding the general expression of uncertainties, a pragmatic approach using covariance matrices related to normal distributions has been justified.

Can position information within a virtual reference frame defined by multiple, heterogeneous Large-Scale Metrology instruments be provided as a service with abstracted interface? – In synopsis, the first research objective is affirmed without restrictions.

4 Protocol-Agnostic Interface Definition for LSM Instruments

To enable flexible system architectures for CaaS and avoid singular software development overhead, an implementation of the individual instruments' interfaces as independent microservices is pursued to investigate the second research question. In traditional automation pyramids, they correspond to field devices in the lower layers, however, in Cyber-Physical Production Systems, the layer-to-layer communication model may be flattened to abandoned (cf. section 5.1). At the same time, the heterogeneity of such systems and their respective interfaces increase the importance of *interoperability*, defined in ISO 2382-1 as »capability to communicate, execute programs, and transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units« [ISO2382, t. 2125481].

For services, EVERTZ et al. deduce three main concerns regarding their interoperability: The representation of data within a communication technology, the order and type of individual items in a message, and the physical meaning and scale of these items [EVER15, p. 2]. Regarding the latter question, an interface model based on a functional view of a Large-Scale Metrology instrument is developed in section 4.2. The first two issues are addressed by networking technologies and IoT protocols. Common protocols are reviewed in section 4.1 to decouple the defined interface model from a specific protocol by establishing a model-based abstraction layer. This allows the realization of the microservice interface using mature and widely supported standards and thereby reduce implementation effort and development environment confinements.

Many existing protocols feature authentication and transport security to allow the establishment of trust on a data transport level. In the context of metrology, traceability generates trust on a physical level, such that a dual trust relation arises. Section 4.3 discusses how traceability can be included on record level for a CaaS system using a distributed ledger approach.

Parts of the work described in this chapter have been published by the author in the following proceedings and journal articles:

Benjamin Montavon, Martin Peterek, Robert H. Schmitt: **Model-based interfacing of large-scale metrology instruments.** Proc. SPIE 11059, Multimodal Sensing: Technologies and Applications, 2019.

Martin Peterek, Benjamin Montavon: **Prototype for dual digital traceability using X.509 and IOTA** CIRP Annals, Volume 69, Issue 1, 2020.

Matthias Bodenbenner, Mark P. Sanders, Benjamin Montavon, Robert H. Schmitt: **Domain-Specific Language for Sensors in the Internet of Production**, Production at the leading edge of technology : proceedings of the 10th Congress of the German Academic Association for Production Technology (WGP), Dresden, 23-24 September, 2020.

From the perspective of the chosen research methodology, this chapter comprises design and rigor cycles addressing the second research question. The exposition to the application domain is embedded into the development of the CaaS reference system in Chapter 7 by relying on the deduced abstraction layer for the integration of different instruments.

4.1 Review of IoT-Protocols and their Applicability

IoT protocols facilitate multilateral interfacing between devices, services and applications by predefining how data is exchanged utilizing an existing network connection. Subsequently, a set of recurring characteristics among established IoT protocols from a practical perspective is identified, using the word message as a descriptor for the entirety of data transmitted, explicitly containing protocol-related overhead [PFRO16, ALFU15, NAIK17]:

Messaging Pattern
In a *Request/Response* pattern, a client initiates the message exchange by sending a request to a server which responds in dependence of the request message's content. Multiple connections occur over separate channels and requests are independent. In contrast, in a *Publish/Subscribe* pattern, channels are shared among multiple entities, such that the communication is initiated by the party sending or listening to a specific message channel, often referred to as topics. Without limitations, a protocol may support one or both patterns. Often a (permanently available) third party, called broker, is employed to decouple the life cycle of a message channel from a specific listening or sending party.

Serialization Model
A minimum ability required to employ a communication protocol is a defined extraction of raw, non protocol-related data from the message. If a serialization model can be defined within the protocol, this means that raw part is directly decoded into typed data fields. In other cases, a serialized representation can always be established adhering to therefore designed schemes such as JSON, XML or BSON.

Authentication and Authorization
Authentication describes the functionality of a protocol to identify the entities participating in the message exchange. The identity information can be used for authorization purposes, i.e. to determine whether the intended message exchange and related data access should be allowed.

Resource Identifiers
Resource identifiers refer to a dedicated part of the message uniquely indicating which information the raw data may contain and to which physical resource it is linked. One can distinguish between structured identifiers representing a hierarchy (e.g. web URLs) and independent, optionally constrained identifiers (e.g. UUID4).

The former may be converted to independent identifiers using injective hash functions.

Model Browsing

If a protocol posses a browsable model not only the raw data is accessible via message exchange but also the underlying resource model and optional metadata can be retrieved via the same interface. The most prominent examples are annotated REST APIs and OPC UA's browsing capabilities.

CRUD Data Interaction

Create, *Read*, *Update* and *Delete* are the basic operations for interfacing from a data-oriented view. A protocol is classified as CRUD-interactive if the messages contain a part attributing the data access method.

Function Invocation

In addition to aforementioned operations, a protocol may offer a method identifying function invocation on the message receiving party. A function is regarded as data interaction that cannot be interpreted as CRUD operation, e.g. leading to physical state changes of a system or data processing before replying.

Table 4.1 assesses these characteristics for a selection of IoT protocols which have been considered during the course of research without claim for completeness and are briefly introduced in the following.

	Publish/ Subscribe	Request/ Response	Serialization Model	Authentication/ Authorization	Structured Identifiers	Model Browsing	CRUD Data View	Function Invocation
OPC UA	✓	✓	✓	✓	✓	✓	◑	✓
MQTT	✓	✗	✗	✓	✓	✗	◔	◔
AMQP	✓	✗	✗	✓	✓	✗	◔	◔
REST/HTTP	✗	✓	◔	●	✓	✓	✓	◕
gRPC	◔	✓	✓	◑	✗	✗	✗	✓
BLE	✓	✓	◑	✓	✗	◑	○	○
MTConnect	✗	✓	✓	✗	✓	✓	◔	✗

Table 4.1: Classification of properties and capabilities of current IoT protocols from an implementing user's perspective. ○ - ● represent the overhead (high - low) of meaningful realizing the respective functionality within the protocol if it is not natively part of the standard.

OPC UA

Open Platform Communications Unified Architecture (OPC UA) is a multi-part specification for a service-oriented and platform independent architecture released by the OPC Foundation in 2008 and undergoing standardization efforts within IEC 62541 [OPC 19]. It defines service profiles, information and address space models to describe an entity's functionality along with a communication stack [HANN08]. The latter abstracts platform-specific implementations behind an API and is mappable to two protocols; a resource-optimized, secured binary protocol and a web service based on HTTP(s) and XML serialization aimed at maximum programming language/tool compatibility. OPC UA has been recommended as technology for the communication layer of the *RAMI 4.0*[1] model.

MQTT

Message Queue Telemetry Transport (MQTT) is a protocol initiated in 1999 and standardized by OASIS in 2013 defining a message transport following a publish/subscribe pattern for entities with a broker acting as middleware [ALFU15, pp. 2354-2355]. Organized in topics, it supports one-to-one, many-to-one and many-to-many routing of messages with three quality of service levels (0, 1 and 2). It relies on the TCP transport and security mechanisms and only has a fixed header of two bytes per message, exhibiting low overhead and leaving the serialization within the raw binary part to the user. Another variant is the *MQTT-SN (Sensor Networks)* specification, which extends the applicability of MQTT to non TCP/IP networks, i.e. for resource-constrained devices.

AMQP

Advanced Message Queuing Protocol (AMQP) originated in 2005 having a strong background in the financial sector and emerged in the ISO/IEC 19464 standard published in 2014 [GEYE14]. Being a binary wire-level protocol, it implies the presence of a reliable transport mechanisms, e.g. TCP. Both point-to-point and publish/subscribe routing are supported, sembling MQTT. In contrast to the latter, it provides enhanced security features, more complex message delivery scenarios (e.g. denials) and advanced integration into multi-tenant scenarios [COHN12]. On the other hand, its complexity and minimal message size of 60 byte result in more resource and implementation overhead. The payload is split into a bare, immutable message and annotation section, with no prescribed serialization of the former [ALFU15, p. 2355].

REST, HTTP & CoAP

The origin of *Representational State Transfer (REST)* is generally attributed to its publication by FIELDING in 2000 but dates back to the *HTTP Object Model* in 1994. It can be regarded as architectural style for client-server systems interacting in a request/response scheme via HTTP with no state being preserved within the system

[1] The term RAMI is derived as abbreviation of »Referenzarchitekturmodell 4.0« published by VDI/VDE-GMA and ZVEI [ADOL15], cf. appendix J.

apart from the representation of resources within the messages [Fiel00, pp. 76-106]. Thereby horizontal scalability, fault tolerance, multi-tenancy, cacheability and portability are favored. Resources should be organized and addressed via URLs, while the messages are expected to be self-describing. The latter is achieved by using a fixed set of HTTP verbs identifying interaction methods, HTTP header fields and typed payloads, e.g. serialized in JSON or XML. The *Constrained Application Protocol (CoAP)* is a subset of REST specified in RFC 7252 aimed at a lower footprint for embedded devices in constrained networks bound to UDP, while maintaining mapping capability to REST over HTTP by its design [AlFu15, pp. 2353-2354].

gRPC

gRPC Remote Procedure Calls (gRPC) is a non-standardized, open-source framework organized by the *Cloud Native Computing Foundation* aimed at performant transferral of function execution across computing systems and programming languages. It is based on binary data transfer via HTTP/2 and by default uses *protobuf* for the serialization of messages, which can be transferred in a request/response or streaming communication pattern [Clou20]. In contrast to other protocols, every interaction is expected to be modeled as function call, i.e. no CRUD method designations exist.

Bluetooth Low Energy

Bluetooth Low Energy (BLE) was included 2009 in the 4.0 version of the Bluetooth standard defining a radio communication technology targeted at mobile devices with low energy consumption. Its network stack contains a *Generic Attribute Profile (GATT)* layer, organizing the transmitted data and serving as a basis for defined device profiles[2]. The tasks of discovery, connecting, pairing and securing are handled independent of the transmitted data within the *Generic Access Profile (GAP)* layer [Mend18, pp. 1234-1235].

MTConnect™

MTConnect™ was introduced in 2008 and later became an ANSI standard, with ANSI/MTC1.4-2018 being the most recent release at the time of writing. It is architecturally designed around agents providing data of devices/assets in XML format via a stateless, read-only HTTP interface. Agents can therefore be regarded as gateways to the proprietary controls. The structure of the XML document and the fields associated to the respective devices are defined manufacturer-agnostic as part of the standard, with a machine tool focus due to the origin of the protocol within that domain. Function calls and authentication/authorization lie outside the scope of MTConnect™ [Vija08].

Field Bus Protocols

Field Bus protocols have been designed to connect field devices to industrial hardware controllers (i.e. PLCs), e.g. *Profinet*, *Ethernet/IP* and *Ethernet Powerlink*. The

[2] A prominent example are BLE devices for healthcare applications, e.g. transmitting blood pressure or medical temperature measurements [Blue20].

domain requirements lead to a focus on reliable realtime communication in closed ecosystems rather than service orientation and broad interoperability. This contrast is reflected in field bus protocols (partially) not relying on IP as implementation of the network layer. Therefore this category of protocols was not evaluated for CaaS in greater detail [JASP04].

Following the objective to decouple the service interface model from the use of a specific protocol, the related processing from the message exchange to a set of explicit actions required by the service implementation is modeled as depicted in Figure 4.1. They can be leveraged to establish a modeling abstraction layer if the offered functions and data, further referred to as resources, is represented in serializable fields organized using unique (preferably structured) identifiers. Table 4.2 explains this set of actions the resource implementation must react to, to which the characteristics of exemplary protocols are matched.

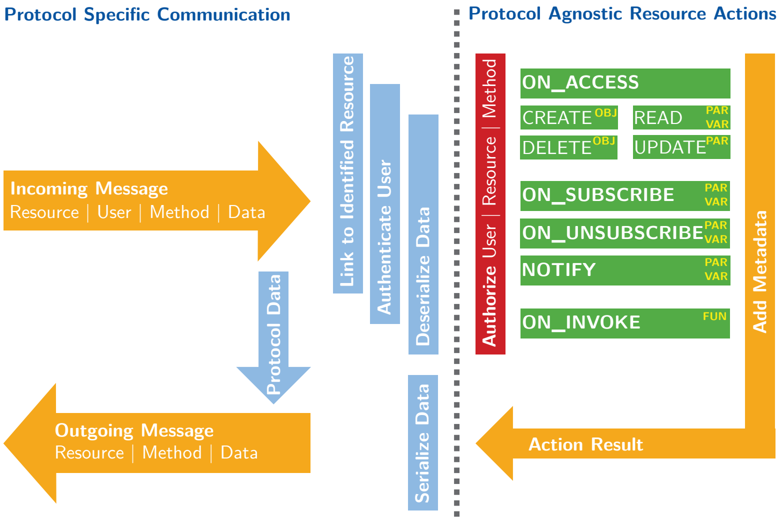

Figure 4.1: Message exchange flow with resource actions: For an incoming message, resource identifier, user and method are extracted from the protocol specific part and the raw data is deserialized to primitive data fields. After an authorization based on the combination of resource identifier, user and method, the action linked to the method is called. It's result is optionally enriched with metadata (e.g. timestamp or nonce) and then serialized to the outgoing message. Protocol specific parts of the protocol may be generated and passed on to the outgoing message without interaction with the resource (e.g. session identifiers). A serialized representation of an internal error occurring during the action is a valid response.

Action		Significance	Example(s)
READ	**VAR** **PAR** **OBJ** **FUN**	Retrieve information on the resource, i.e. meta-data and current value for variables and parameters.	HTTP GET, OPC UA read, BLE read characteristic
UPDATE	**PAR**	Set a parameter's value. If this is not meaningful (i.e. for protected parameters), the authorization logic should return read-only permissions.	HTTP PUT, OPC UA write, BLE write characteristic
CREATE	**OBJ**	Update the device/service by adding a resource.	HTTP POST, OPC UA register node
DELETE	**OBJ**	Update the device/service by removing a resource.	HTTP DELETE, OPC UA delete node
ON_SUBSCRIBE	**VAR** **PAR**	Add a recipient to value update notifications of the variable respectively parameter.	MQTT subscribe, gRPC stream, OPC UA subscription, AMQP attach
ON_UNSUBSCRIBE	**VAR** **PAR**	Remove an update recipient.	MQTT unsubscribe, AMQP detach
NOTIFY	**VAR** **PAR**	Callback dispatching value changes to recipients.	MQTT publish, AMQP transfer
ON_INVOKE	**FUN**	Invoke an implemented function.	OPC UA method call, gRPC call

Table 4.2: Overview of resource actions and their significance to objects, variables, functions and parameters. Depending on the messaging pattern, only a subset of actions is called. ON_SUBSCRIBE and ON_UNSUBSCRIBE may be delegated to a protocol-specific message broker. The provided examples are non-exclusive.

To further reduce complexity, a division of resources into *Objects (OBJ)*, *Functions (FUN)*, *Variables (VAR)* and *Parameters (PAR)* only offering specific subsets is proposed: Objects provide an object-oriented data view and in combination with structured identifiers are the only resources allowed to posses subordinate child items. Variables encapsulate access to data with physical origin, e.g. measurements, which are naturally read-only. Therefore parameters separately encode read and potential write access to primitive data fields. Functions are resources that are callable with a set of argument and return values, leading to a function invocation on the resource as defined above. The parameter resource class is reused to represent the arguments respectively return values as children of the function resource. Moreover, each resource class is associated with a set of metadata as stated in Table 4.3.

Name	Description	OBJ	PAR	VAR	FUN
UUID	Unique identifier among the children of the parent object which can be concatenated over hierarchy levels to a fully qualifying identifier.	●	●	●	●
Name	Human readable name, primary for user interaction purposes.	●	●	●	●
Description	Human readable description, also primary for user interaction purposes.	●	●	●	●
Ontology	Machine readable ontology identifier for automated discovery.	◑	◑	◑	◑
Datatype	Standardized datatype of the value, e.g. limited to float64, boolean, int64, string, time or enumeration.	○	●	●	○
Dimension	Dimensionality of data representation, especially for multi-valued data, e.g. vectors and matrices.	○	●	●	○
Range	Limits of valid values the resource can represent.	○	◑	◑	○
Timestamp	Time of data acquisition/last update of the held value.	○	◑	●	○
Covariance	Covariance of the value, if applicable.	○	○	●	○
Unit	Unit of the data in standardized format (e.g.UNECE).	○	◑	●	○
Nonce	User-defined label for arbitrary purpose.	○	○	●	○
Hash	Optional field for signatures of the data/metadata package, cf. Section 4.3.	○	○	◑	○

Table 4.3: Metadata set considered with its applicability to different resources classes: ● - mandatory, ◑ - optional, ○ - not applicable. An exemplary serialization is contained in Table 4.4.

Authentication is treated as protocol-specific task, while authorization interpreted as resource-specific question if an action is allowed for a specific combination of user and resource identifier and therefore not discussed in further detail.

With the defined abstraction layer, a device or service whose resources can be modeled in objects, function, variables and parameters for which its internal software implements the respective subset of actions can be linked to any arbitrary protocol using methods expressable as aforementioned actions and handling resource identification, authentication and serialization. Moreover, simultaneous interaction over multiple protocols is enabled and facilitates integration into heterogeneous environments. Table 4.4 shows an example of a variable resource's data representation being serialized in response to a read or notify action in two different ways[3].

On this basis, the use of multi-protocol routers is enabled, which in general underlies the following assumptions:

- A bijective mapping of address spaces for unambiguous resource identification exists
- Authentication and authorization adhere to the same user database
- To interoperate between request/response and publish/subscribe messaging patterns, a CRUD enabled data storage with update callbacks is available
- Individual protocol methods are explicitly assignable to data respectively function interactions
- All serialization schemes and their used data types are mutually compatible
- Errors are treated consistently
- Manual configuration/conversion rules may be required but are kept to a minimum

Approaches for multi-protocol routers have been presented respectively implemented within the Eclipse *Kura* (MQTT, REST, OPC UA, BLE) and *Ponte* (MQTT, REST, CoAP) software projects as well as in scientific works by Pfrommer et al. (OPC UA, REST) and Desai et al. (MQTT, REST, XMPP) [Pfro16, Desa15]. Moreover the commercial products *KEPServerEX* (OPC UA, REST, MQTT, ODBC) by PTC Inc. and *XI-Gateway* (MTConnect™, OPC UA) by PROXIA Software AG offer protocol routing capability [PTCI20, PROX18]. Within the course of research related to this thesis, a multi-protocol routing application was developed in cooperation with a major network equipment manufacturer, targeted to run on network access points or switches and potentially also acting as edge gateway. The application's logic and architecture is summarized in Figure 4.2 and recapitulates the principle of protocol translation.

[3] For an example of a model elaborated using the deduced abstraction layer, the reader should refer to the upcoming section.

[0:Root, 0:Objects, 1:BLEnv, 1:Sensor_0x0192, 1:Temperature]	
NodeId	s="BLEnv/Sensor_0x0192/Temperature"
NodeClass	Variable
BrowseName	1:Temperature
DisplayName	Temperature
Description	Current ambient temperature in degree celsius.
Value	21.0
ServerTimestamp	None
SourceTimestamp	2019-03-16T22:52:04.000000Z
DataType	Double
ValueRank	Scalar
ArrayDimensions	None
AccessLevel	CurrentRead
UserAccessLevel	CurrentRead
Historizing	False
References	{HasType: [0:Root, 0:Types, 2:WZL, 2:Ambient, 2:Temperature]}

OPC UA: Variable node attributes adhering to the OPC UA standard node class definitions. The data is serialized in a protocol specific XML-based or binary format. The node as resource is identified via a browse path containing a server-related (prefix 0:) and custom namespace (prefix 1:. Ontologies are represented through type nodes within the address space which are linked to the variable node.).

objects/OBJ-BLEnv/OBJ-Sensor_0x0192/VAR-Temperature/

```
{
    "uuid" :          "VAR-Temperature",
    "name" :          "Temperature",
    "description" :   "Current ambient temperature in degree
                      celsius.",
    "value" :         21.0,
    "timestamp" :     "2019-03-16T22:52:04.000000Z",
    "covariance":     [0.25],
    "unit":           "CEL"
    "datatype" :      "double",
    "dimensions" :    [],
    "nonce" :         "PhD-Thesis"
    "hash" :          null
    "ontology" :      "WZL:Metrology:Ambient:Temperature"
}
```

JSON: Variable resource serialization using JavaScript Object Notation, applicable to any protocol allowing custom serialization and widely used in for HTTP/REST, MQTT and AMQP. The identifier is a hierarchical URI.

Table 4.4: Different serialization examples for a possible response to read action for an ambient temperature sensor.

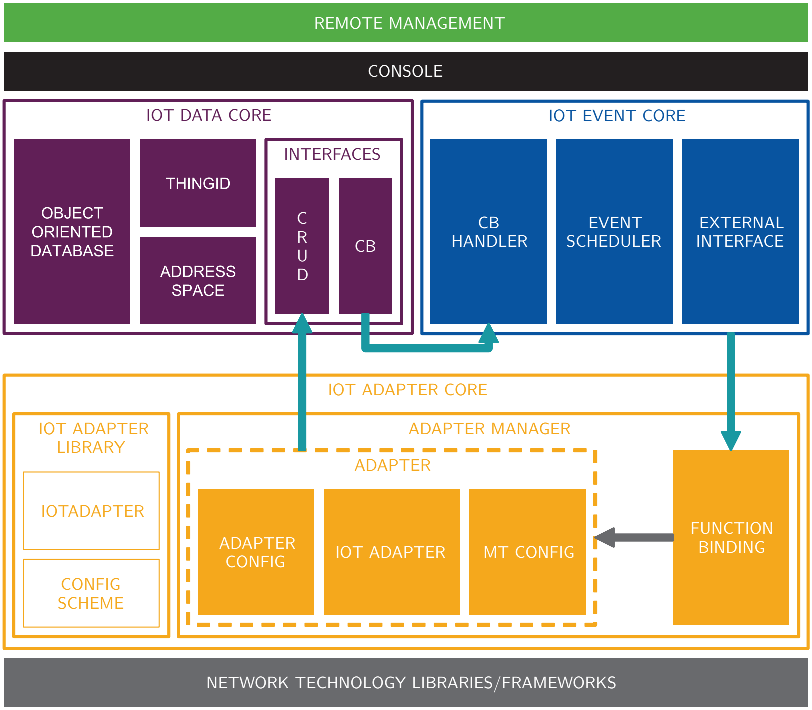

Figure 4.2: Architecture and logic of the implemented protocol router. The IoT adapters implement the relation of the individual IoT protocols to the common core. The interaction methods are translated to CRUD operations on the data core including the transition to a common hierarchical and unique address space and execute the according database action. This triggers a callback which enters the event core, which can also be triggered by external events (e.g. timers). The IoT adapters subscribe to the event core and dispatch updates where appropriate (e.g. to MQTT subscribers). Configuration nodes contain additional settings required but not directly related to the routed data. The author acknowledges the support of the works of Dejan Boberic as basis for this figure.

4.2 Model-Based Interface Definition

As deduced in the previous section, the interface implementation of a Large-Scale Metrology instrument can be decoupled from a specific protocol if its functionality is modeled in objects, functions, variables and parameters as resources. Most critical to this model are its properties of pragmatism as defined by STACHOWIAK [STAC73, p. 132]: Its *audience* is determined by CaaS consumers interacting with the individual instruments. Subsequently, the *validity period* must comprise the actual measurement activity of the instrument, while configuration and maintenance may be indicated as state but can remain opaque due to the limited interest of the audience. Finally, the *defined scope of interaction respectively operation* is determined by the abstract functionality of Large-Scale Metrology instruments from the audience's perspective. This favors a functional modeling view over a view oriented along the physical embodiement of the instrument as only the former is able to uniformly model different devices and principles providing identical respectively similar capabilities, which in turn is required for interchangeable use[4].

Aiming at CaaS with instruments as recomposable microservices and recalling Definition 1.3 for Large-Scale Metrology instruments, a functional view around the position information of the instrument's mobile entities emerges as core element of a possible model-based interface. At the same time, FRANCESCHINI et al. classify LSM instruments according to their hardware organization into *distributed*[5] and *centralized*[6] systems [FRAN14b, p. 1744]. This offers an entry point to a physical perspective for the interface if centralized systems are conceived as possessing exactly one measuring station at their origin. Both approaches are combined in the interface model proposed in Figure 4.3 using an object-oriented approach with base stations and mobile entities as types. The former are instantiated by the measuring stations of the instrument, e.g. indoor GPS transmitter, ultra-wideband communication anchors or a laser tracker head. Instances of the latter are the mobile units whose positions are actually determined by the instrument, e.g. PCEs of an indoor GPS or SMRs for a laser tracker. These provide the interface to their current position information, regardless whether they are passive or active units[7]. This perspective also foresees probe tips respectively functional points of CMM's and calibrated machine tools with fixed kinematics as mobile entities. An overview of the resources attributed to the mobile entity type including their significance is listed in Table 4.5.

[4]For the simple example of a traditional 6DoF robot these perspectives translate to either modeling its position command interface as six individually controllable joints or as kinematic capable of moving its tool center point in three directions and rotate around three axes. While the first view may result in a more accurate description of a single device and its specific functions, the latter perspective offers the advantage of uniformly modeling different kinematics.

[5]»A distributed system consists in a series of measuring stations that work cooperatively to collect information for determining point coordinates. In general, the individual stations cannot measure coordinates separately. Individual stations may be identical devices, or alternatively different kinds of devices (US devices, IR devices, cameras, etc.), distributed in the measurement volume.«[FRAN14b, p. 1744]

[6]»A centralized system is essentially a stand-alone unit which can work independently to provide the measurement of a spatial coordinate on the object surface, e.g., a laser tracker. In some cases, a number of centralized systems can be used simultaneously with the aim of improving measurement accuracy.«[FRAN14b, p. 1744]

[7]For example, the position of an SMR is measured by the angular encoders and the distance measurement system in the laser tracker head, although it is interfaced via the SMR's object instance.

Figure 4.3: Structural overview of the unified Large-Scale Metrology instrument interface developed. The structure can be extended by specific implementations, as long as it contains the presented hierarchy to adhere to the proposed unification. The calibration certificate identifier is assumed to be a string unambiguously identifying a digital calibration document for the instrument and/or respective component (e.g. supplementary calibration information for an SMR) as further discussed in Section 4.3.

FUN-Reset ($\emptyset \rightarrow \emptyset$)
Reset the entity to its initial state.
Laser Tracker: Restore the initial position of the reflector.
Indoor GPS: Call the PCE(s) internal reset function.
FUN-Trigger (int *count*, string *nonce* $\rightarrow \emptyset$)
Trigger the entity to measure *count* times and set the internal nonce to *nonce*. This call is only valid for an active target in triggered acquisition mode.
Laser Tracker: Dispatch the next *count* valid measurement results and associate these with target in question.
Indoor GPS: Dispatch the next *count* updates of the PCE(s).
PAR-Mode (enum {CONTINUOUS, TRIGGERED, EXTERNAL, IDLE})
Current state of the entity. In CONTINUOUS mode, values are dispatched as fast as possible. In TRIGGERED mode, values are only dispatched after a software trigger. In EXTERNAL mode, values are dispatched in accordance to an external trigger, e.g. probe or TTL. IDLE means the entity is currently not used.
PAR-Type (string)
System specific identifier of the target Type, e.g. iProbe.
PAR-Name (string)
Human readable name of the target.
PAR-State (enum {OK, WARNING, ERROR, MAINTENANCE})
Reflects the mobile entity's system state.
VAR-Position (double[3])
Last measured position of the target in metres.
VAR-Orientation (double[4])
Last measured orientation of the target as quaternion, if available.
PAR-Calibration (string)
Unique identifier that can be used to retrieve a corresponding calibration certificate.

Table 4.5: Description of the variables (VAR-), functions (FUN-), parameters (PAR-) and objects (OBJ-) of the mobile entity type class with example function mappings for indoor GPS and laser tracker.

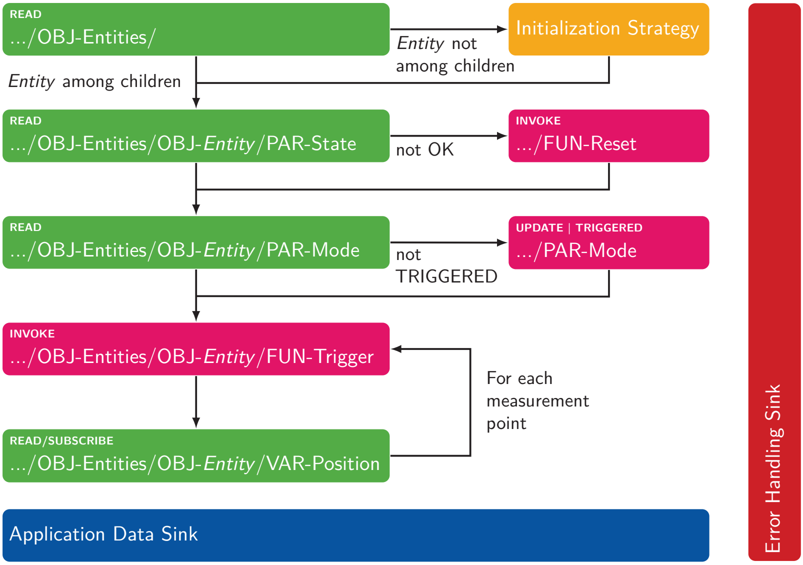

Figure 4.4: Minimal interaction flow with a Large-Scale-Metrology instrument service for a software-based triggering consumer. Application paths not foreseen in the standard flow should be treated by an error handling system.

Probes are functionally not covered[8] by the proposed model as they are interpreted as devices themselves which rely on one or more target entities at defined physical interfaces. Moreover, a single instrument may be used with different types of probes of which may not all be known to the manufacturer. Following the microservice paradigm, a tactile coordinate measuring system could be realized by a superordinate software accessing the position information of the LSM instrument over its interface after a trigger signal has been received from the probe. Figure 4.4 summarizes the general interaction flow for a triggered use of an instrument in an arbitrary application: At first, the presence of an object representing the envisaged entity is verified, before checking whether it is not in a function inhibiting state and setting its operation mode to TRIGGERED. The core operation loop consists of invoking the software trigger function and subsequently reading the updated value and metadata for the position variable.

[8] A probe is partially covered by the model if in the perspective of the mobile entity in question it acts as its physical reference point, however this does not apply to its details, e.g. tip radius.

An object is interpreted as type instantiation if it contains all functions, parameters, variables and child objects of the type definition. This allows to add device-specific (e.g. inferred from a physical view) resources to the individual model-based interface while maintaining the generic functional perspective, e.g. adding digital in- and outputs of PCEs as parameters. Especially regrading the loosely defined *Large-Scale Metrology Object* and *Generic Device Object* (cf. Figure 4.1), adding additional resources allows for seamless embedding of the proposed interface into more complex device models. Appendix C describes the further resources of the default interface model.

4.3 Consideration of Traceability Information

In complex Cyber-Physical Production Systems, of which CaaS is expected to be part of, a need for digital traceability on a dual level prevails: From a computer science perspective, posterior or malicious modification of the data should not be possible without being detectable, among others in the form that data processing streams can be reconstructed from the data origins at any time [PENN19, p. 35]. In parallel, traceability from a conventional metrology point of view is motivated by physical compatibility of a measurement with a need for documentation inferred by the associated chain of calibrations (Definition 1.2).

Both concerns can be addressed on record[9] level as summarized in Table 4.6 leveraging the model-based interface defined above, distributed ledger techniques and digital approaches to calibration certificates found in literature. The use of distributed ledger technologies in the domain of metrology is proposed by MELO et al. in the context of cloud measuring systems [MELO18, MELO19], naming *distributed measuring* and *decentralized supervision* as prospects. The first aims at reducing sensors to minimal analog-to-digital converters publishing raw data in transactions and realizing subsequent computation as smart contracts to preserve data integrity through the nature of a blockchain. Supervision embraces data analytics to assess the sensor's condition based on the published data. Permissioned blockchains are proposed as solution to the associated privacy problems for sensible data. The approach was validated on a system constituted by distributed vehicle speed meters. Concepts to use blockchain technologies to represent the chain of calibrations associated to conventional traceability are outlined by AIMAGMBETOVA et al., TAKATSUJI et al. and SHAH et al. with the latter presenting a prototype based on Ethereum smart contracts [AIMA17, TAKA19, SHAH19]. PETERS et al. introduce blockchain technologies as basis for decentralized audit trails for measurement equipment proposing log entries and persistent data are issued as transactions [PETE18].

[9] A record is conceived as position information and associated metadata as result of an individual coordinate measurement, cf. Table 4.6.

Information	Datatype	Necessity
Value	n `float64` fields	Access to the measurand's value of n dimensions.
Covariance	n^2 `float64` fields	Covariance matrix belonging to complete measurement result.
Unit	3 unicode `char` fields	UNECE compliant unit identifying code to physically interpret the value.
Time	11 `bytes`	Timestamp in UTC according to RFC3339 (year, month, day, hour, minute, second, nanosecond)
Nonce *optional*	$\leq$ 255 unicode `char` fields	User-definable string serving as arbitrary label.

Table 4.6: Record content as subset of a model-based representation of a sensor's interface to the measurand. Order and explicit computational type are critical for cross-platform interoperability with consistent hash generation. The record's content is similar to the proposal of HACKL et al. considering the uncertainty expression discussed in section 3.4 [HACK18].

The *Digital Calibration Certificate (DCC)* was introduced under this name by PTB and is further investigated in an European Consortium at time of writing. The objective is to provide a solution for »[...] electronic storage, the authenticated, encrypted and signed transmission and the uniform interpretation of calibration results [...]« [WIED18, EICH18]. Most prominent is an XML-based document as digital representation with a regulatory section containing (at least) the same information as a conventional calibration certificate issued on paper. Further sections cover measurement results (partially regulated), comments (unrestricted) as well as a built-in PDF-A representation. In addition, signage and encryption of the according documents as well as the implementation of retractability are discussed using an appropriate authority or another blockchain approach [HACK18].

Figure 4.5 summarizes a proposal to introduce data traceability on record level: The comment section of the DCC can be exploited to include an X.509 certificate with according public key and associated private key additionally issued by an appropriate public key infrastructure[10] after successful physical calibrations. The private key can then be used to cryptographically sign a fingerprint of a measurement record. Therefore a fixed definition of a record's content and a platform-agnostic, unambiguous binary serialization scheme are necessary. This is achieved by defining the content as subset of the model-based interface's variable definition with explicit types and order as proposed in Table 4.6, leading to a byte wise determin-

[10] A prominent example for public key infrastructures are web server certificates for HTTPs communication, which are typically issued through a chain of certificate authorities deriving from a trusted root authority.

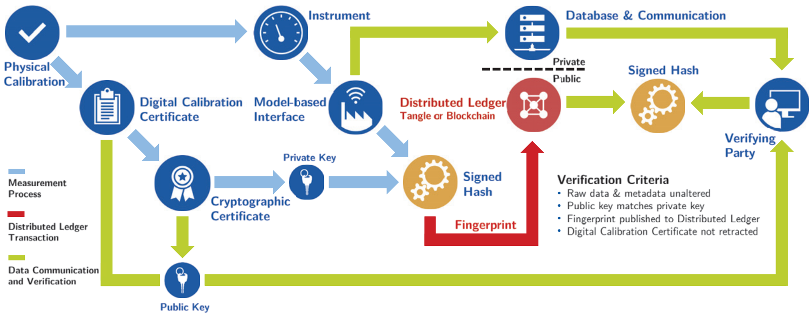

Figure 4.5: Summary of the proposed dual digital traceability approach. After a successful physical calibration, a digital and cryptopgraphic certificate are issued. The private key of the latter is used to sign a hash of a fixed subset of a model-based sensor data record and the signature is published to a distributed ledger. With private communication of the sensitive raw data, a verifying party can reconstruct the hash and verify its published signature using the public key of the cryptographic certificate.

istic representation that can enter a widely-available fixed-length hash function, e.g. SHA-256 [NIST15]. The signed fingerprint is eligible for publication in a transaction to a distributed ledger, even for sensible data, as reconstruction is virtually impossible. Any party obtaining full data of the record and digital calibration certificate with public key can check the data's integrity by rebuilding the fingerprint of the record and verifying its signed counterpart retrieved from the distributed ledger. For practical implementations, a non-hashed tag should be added to the transaction to facilitate later retrieval. With a bijective relation of digital calibration certificates and cryptopgraphic certificates, retraction of the former can be detected through the inability of unrecognized certificate substitution and proposed validation schemes native to the DCC. An explicit link to the instrument interface elaborated in the previous section is envisaged through string-based unique identifiers of the according DCCs, which, if not natively available, can also be included into the comment section.

A prototype of the proposed approach leveraging the protocol-agnostic interface to Large-Scale Metrology Instruments has been implemented using *OpenSSL* for certificate generation and *IOTA* as distributed ledger [POPO18] and is summarized in Figure 4.6. While the applicability of the approach was validated, a technical limitation was imposed by the performance of the public development tangle used and is not expected in production scenarios, e.g. where the distributed ledger is provided as part of a intercorporate data infrastructure. Considerations of the latter are regarded as subject to development and outside the scope of CaaS. Moreover, when such an ecosystem is established, further research questions regarding new business models for traceability activities and how data integrity concerns through subsequent algorithms can be integrated into distributed ledger techniques arise.

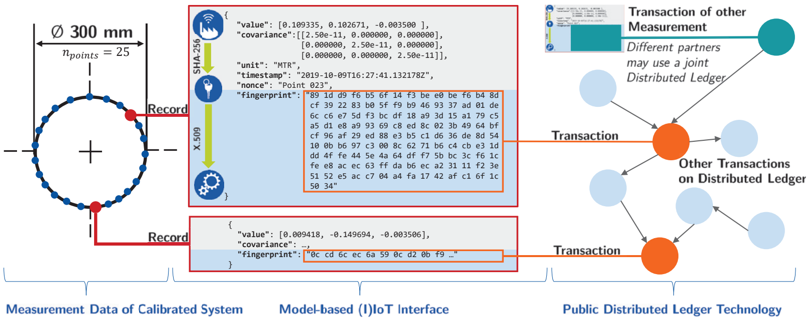

Figure 4.6: Schematic representation of the evaluated prototype for dual digital traceability: Each measured point, here depicted as probing points of a circular feature, are represented as record with contents according to Table 4.6. Its binary serialization is then hashed and signed and a representation in JSON including the fingerprint is generated. The fingerprint then enters a public distributed ledger, which corresponds to a IOTA transaction in the case of the prototype.

4.4 Intermediate Summary

Reviewing established IoT protocols based on scientific literature and knowledge gained through practical application, their eligibility to contribute to the interoperability efforts has been confirmed. Moreover, the analysis of recurrent properties has been applied to establish a protocol-agnostic abstraction layer providing a framework to model resources with predefined action and metadata sets to reduce complexity. The latter has subsequently been used to define a reference model for interfacing Large-Scale Metrology instruments from a technology-agnostic, functional perspective, although this approach comes at the cost of omitting capabilities of individual protocols. Its adequacy for implementation and application is confirmed in the CaaS demonstrator system described in Chapter 7 for multiple instruments and consumers. A design weakness currently identified is the incorporation of instruments effectively measuring point clouds (e.g. laser radar), for which a dedicated mobile entity type should be considered in future research[11]. From an implementing perspective the two advantages of CaaS technically not being limited to a single protocol and individual instruments implementations being decoupled from their integration into CaaS[12] to a large extent are maintained. The entity-centric modeling perspective is complemented by a capability model in Chapter 6. This separation is motivated by the different requirements to a Large-Scale Metrology instrument model depending on the state of the applica-

[11] In its most simple realization, the dimensions of VAR-Position and its according covariance could be increased to $[n_{points}, 3]$ and $[n_{points}, n_{points}, 3, 3]$.

[12] A dependency is inevitably introduced if authorization policies are enforced with respect to a central instance.

tion, i.e. changing among conceptualization, simulation and operation, which also reflect in different requirements regarding communication, instrument availability and computational capabilities.

Can a model-based, protocol-agnostic interface to Large-Scale Metrology instruments be defined based on technology-independent characteristics? – Based on the intermediate summary, the second research guiding question is approved. In addition, a concept to link the concern of dual digital traceability has been elaborated and prototyped, further supporting the chosen approach to interface the individual Large-Scale Metrology instruments.

5 Architecture of a Virtual Service-Oriented Metrology Frame

The third research question highlights the need for an appropriate architecture for the implementation of CaaS systems as part of the overall design cycle. Predominant requirements are scalability in terms of coverage and number of participating instruments, resilience against failure of individual components as well as practical applicability. Furthermore, metrological capabilities of the individual instruments should not be deteriorated by their CaaS integration. Following a brief discussion on architecture recommendations for Cyber-Physical Production Systems in Section 5.1, a separation of subtasks in CaaS for an implementation as microservices is carried out in Section 5.2. Subsequently, a non-exclusive architecture proposal distributing the microservices among four layers is elaborated in Section 5.3.

5.1 Evaluation of Existing Architecture Approaches for Cyber-Physical Production Systems

Envisaging the integration of CaaS into complex Cyber-Physical Production Systems, the same challenges regarding IT requirements and architectures prevail: The number of entities being connected and containing a digital respectively virtual counterpart is constantly increasing. Mutually requested information and distributed control paradigms lead to layer-wise information transfer becoming insufficient and gradual dissolution of traditional automation pyramids [ÅKER18]. In addition to growing technical requirements, organizational adaptions of software development and deployment are required given their increasing velocity and number of participants. GÖTZ et al. summarize differences between traditional and emerging manufacturing IT as cited in Table 5.1 and identify the lack of flexibility and scalability as main drawbacks of monolithic architectures typical to traditional manufacturing IT [GÖTZ18]. In the academic context of CPPS, their dissolution can be recognized in mutually non-exclusive design approaches based on *holonic manufacturing systems*, *multiagent-based systems* and *microservices* [RIBE18].

Preliminary parts of the work described in this chapter have been published by the author in the following proceedings article:
Benjamin Montavon, Martin Peterek, Robert H. Schmitt: **Communication architecture for multiple distributed large volume metrology systems.** 2017 IEEE International Systems Engineering Symposium (ISSE), 2017.

Traditional manufacturing IT	**Emerging manufacturing IT**
Hierarchical	Non-hierarchical networks
Centralized	Decentralized
Software suites	Services, Apps
Monolithic	Fine-grained services
License-Fees	Pay-per-Use
Complex integration	Open standards
Delayed data	(Near) real-time data
Roll-out within months/years	Deployment within minutes

Table 5.1: Comparison between traditional and emerging manufacturing IT carried out by GÖTZ et al. [GÖTZ18].

VAN BRUSSEL et al. introduce a consortial definition of a holon as »An autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon.« [VANB98, p. 256]. Exemplary, their architecture recommendation consists of order, product and resource holons as basic building blocks of a holonic manufacturing system, with the latter block being defined as holding »[...] the methods to allocate the production resources, and the knowledge and procedures to organise, use and control these production resources to drive production.« [VANB98, p. 257]. From this perspective, a CaaS system can be attributed the role of a resource holon. However, their technical materialization is conceptually not further specified.

Multiagent-systems are a frequently discussed architecture approach to the implementation of distributed control systems reaching down to the level of field devices. CRUZ et al. provide an extensive review, identifying four common agent functionality patterns [CRUZ19]: Resource access, i.e. the encapsulation of interaction with field devices such as sensors and actors; Coordination process, i.e. management of components, scheduling and resource capability monitoring; Knowledge base, i.e. incorporation of virtual models and databases as additional decision backbones; and Communication interface, i.e. enabling and abstracting communication among all components in the systems. RIBEIRO et al. explicitly state the complimentary nature of multiagent-systems and service-oriented architectures as automation paradigms highlighting their difference in behavior description: While services are rather described by their public interface and execution details remain opaque, agents are characterized by a description of their logic behavior using established methods [RIBE08, p. 265]. Attributing agents the role of implementing the application logic in cyber-physical control loops, CaaS is not conceived as agent-based system but as infrastructural, service-oriented resource to the latter a priori not implementing actions with effects outside its own scope. Consequently, it should specify public interfaces exposing the information required by the typical agent patterns previously described.

Considering the hitherto argumentation, an approach to design CaaS as an aggregated system of microservices is followed. The aggregation is expected to cooperatively deliver the envisaged service characteristics with possible interaction between the individual microservices if necessary. Among others, the benefits of microservices in an industrial context are generally discussed by GÖTZ et al. to embrace challenges in emerging manufacturing IT (cf. Table 5.1) and evaluated in literature on different scales, e.g. for knowledge management or the implementation of a Computerized Numerical Control (CNC) system [GÖTZ18, SCHÄ18, AFAN17]. From a broader perspective across various domains, microservices are an increasingly popular paradigm in software and system architecture design. Although multiple definitions are possible, their main characteristic is that they encapsulate a concise functionality as a small independent software module with well defined network interface while keeping the implementation opaque to other parties in the wider system. In the original domain of software engineering, JAMSHIDI et al. cite faster delivery, improved scalability and greater autonomy among their key benefits [JAMS18, p. 25]. These advantages can be translated to CaaS systems in the following way:

- Scalability is required in terms of the number of instruments respectively mobile entities acting as resources and the number of consumers interacting with the service. From a metrological point of view this also includes scalability with respect to the service's operating volume as well as the requirement that the integration of an instrument into a CaaS system must not deteriorate its performance at any time.

- Greater autonomy allows individual components to be implemented and operated not only by different teams but also by different institutions. The opaqueness of the implementation facilitates the preservation of intellectual property, especially considering functionalities relying on elaborated instrument and process models. Moreover, the autonomy of components directly influences the resilience of the overall system against the failure of individual components.

- Faster delivery is reflected by the ease of integrating new instruments and consuming applications as well as the ability to establish a continuously working CaaS system while further developing single components.

In addition, from an organizational point of view, the non-monolithic implementation design allows for improved and audience-tailored design of user interfaces to CaaS itself and relying applications. Due to the wide, cross-domain adaption of the microservice philosophy, a large number of potentially reusable soft- and hardware platforms is available.

5.2 Dissection of Concept Components into Microservices

To leverage the aforementioned benefits, a dissection of the different required subtasks within a CaaS system into mostly independent microservices presented below is proposed. At the same time it should be stated the approach is non-exclusive and other designs may be applicable to a successful CaaS implementation as well.

Instrument Microservice(s) $\mathbb{I}$
The functionality respectively operation of the individual Large-Scale Metrology instruments is encapsulated in microservices as defined in Chapter 4.

Explicitly Expected Interfaces

- Objects, parameters, functions and variables as outlined in Figure 4.3 using at least one standardized protocol providing the necessary resource actions.

Instrument Modeling Microservice(s) $\mathbb{M}$
The appropriate estimation of the expected covariance and other characteristics discussed in Section 6.1 requires implemented, queryable models of the instruments. As the mathematical formulation may be opaque to the relying parties, this requirement effectively instantiates a microservice. This component is a prominent example for a situation where the microservice may be provided on an external platform, e.g. hosted online by the instrument's manufacturer or a national metrology institute.

Explicitly Expected Interfaces

- Boolean visibility function $\mathcal{B}(\hat{\boldsymbol{p}})$ as defined in Chapter 6.
- Angular acceptance function $\mathcal{Q}(\hat{\boldsymbol{p}}, \hat{\boldsymbol{n}})$ as defined in Chapter 6.
- Covariance estimation $\hat{\mathbf{V}}(\hat{\boldsymbol{p}}, \hat{\boldsymbol{q}})$ as defined in Chapter 6.

User Service $\mathbb{U}$
Consistent authentication and authorization among multiple microservices requires a shared user directory, which is regarded as a service by itself. It is expected that in many cases a centralized accounting system will be available independently of CaaS.

Explicitly Expected Interfaces

- Authentication based on username and password verification.
- User information retrieval, i.e. attribute or role description for authorization purposes.
- Token generation and verification for substitutional credential usage.

Entity Management Microservice $\mathbb{E}$

This microservice maintains records of the instruments' entities available to the CaaS system including their properties summarized in Section 6.1 and the coordinate transformation parameters defined in Chapter 3. Therefore it relies on the instrument modeling microservice(s) $\mathbb{M}$.

Explicitly Expected Interfaces

- CRUD access to known entities and their details as defined in Table 6.2.
- CRUD access to known instruments and their interfacing details (e.g. network address, protocol).
- Read and update access to coordinate transformations as defined in Chapter 3.

Allocation Microservice $\mathbb{A}$

The formal resource allocation business consists of ensuring that no interference between multiple consumers using the CaaS with individual instruments as resources occur, mainly by keeping track of access requests over time. In consequence, the allocation microservice must provide an interface both to consumers demanding an allocation as well as instrument microservices checking the access right on a consumer[1]. In the case of user-grained authorization scenarios, this microservice may interact with the user service.

Explicitly Expected Interfaces

- Read access to existing entity allocations with ability to apply a time filter Δt.
- Explicit allocation request endpoint specifying the entity in question by a primary key, a time span Δt, an associated user and access level, optionally returning an allocation token.
- An optional endpoint implementing allocation token verification.

Planning Microservice $\mathbb{P}$

As discussed in Section 6.3, the actual choice of entities is a multi-constraint optimization problem. Its encapsulation as a microservice allows to defer this task to a superordinate resource management system, while an implementation within the CaaS system is still possible and necessary to deliver position information as a service result to arbitrary consumers.

Explicitly Expected Interfaces

- Access to a ranked list of entities according to the ranking metric defined in Section 6.3.

[1] The envisaged interaction flow with $\mathbb{A}$ is that it issues tokens to consumers when granting access to one or multiple instruments which can be verified by the instrument microservice. The latter step is optional if no malicious requests are expected.

- Access to a combined, ranked list of entities and shop floor regions according to the discretized ranking metric defined in Section 6.3.

Consumer Microservice(s) $\mathbb{C}$
Any application utilizing the CaaS system and the above mentioned components is regarded as a microservice on its own, which either directly interacts with human users and agents to physical actors or represent services themselves, e.g. persistent data storage and analysis or geometric characteristic evaluation.

Explicit interfaces to be defined by the consumer

External Microservice(s) $\mathbb{X}$
To maintain compatibility, any custom extension or modification to the CaaS system is encouraged to be implemented as a separate microservice rather than substituting one of the base services. Moreover, this software design facilitates the development of third-party modules. An example could be an application analyzing the expected visibility impacts on optical measurement instruments based on current CAD-models of the shop floor.

Explicit interfaces to be defined by the external microservice

5.3 Implementation of CaaS in a 4-Layer Architecture

Apart from the dissection in microservices, resilience, scalability and performance of an implemented CaaS system depend on the composition of the microservices on individual hardware layers with according computing and networking capabilities. Therefore a four-layer architecture presented in Figure 5.1 is proposed whose prospects will be discussed layer- and service-wise in further detail: The base level is constituted by the instruments itself. With their individual hardware, scalability and resilience of the overall system are naturally available as long as they act independently. The software is limited to the proprietary core functionality required to operate the instrument as a measuring device and unaware of the integration into CaaS system. The latter is achieved by means of the second layer, which encapsulates the instrument's immediate software with an interface adhering to the models elaborated in Chapter 4. Moreover, it explicitly acts as a network gateway on hardware and protocol level and can thereby be classified as application of edge computing. Depending on the computational hardware an instrument uses, the first and second layer may run on the same platform, e.g. an embedded industrial PC or PLC. However, their conceptual separation allows the local use of specific technologies (e.g. high-bandwidth image acquisition and processing or ultra-low-power sensors) and facilitates the interchangeable design of model-based service interfaces.

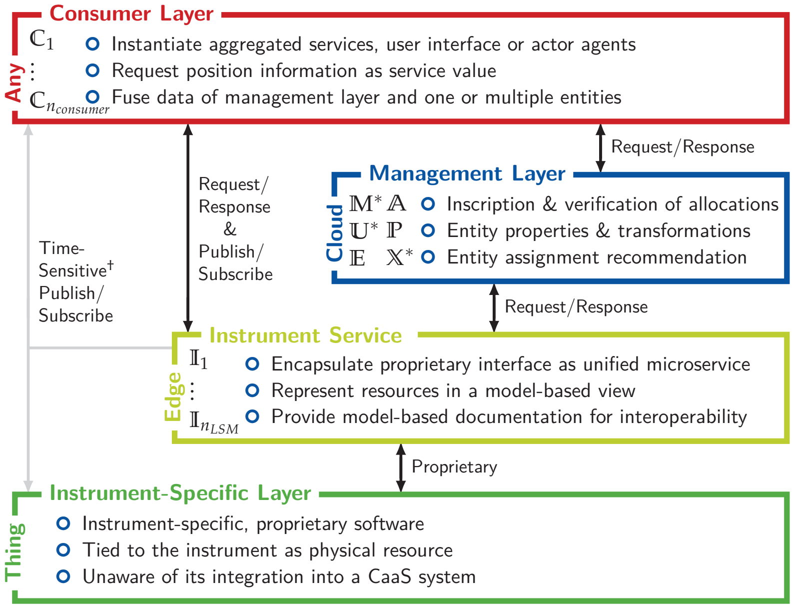

Figure 5.1: Distribution of the microservices identified in Section 5.2 among four layers with the respective tasks they are expected to fulfill and the typical messaging patterns. Services marked with $(*)$ may be run by an external provider. Time-sensitive (†) refers to direct communication with minimal networking overhead, latency and jitter. This layer model is considered to be semantic without the inhibitance of direct communication among individual entities.

The network gateway is also regarded as in charge of time-synchronization[2] given the availability of suitable protocols, i.e. NTP and PTP, to achieve synchronization on a microsecond level [GIRE20] and current efforts to integrate these with wireless 5G communication [MAHM19].

Most of the microservices discussed in the previous Section reside in the management layer, including all functionality of a CaaS system which does not require instrument interaction, e.g. resource management as discussed in Chapter 6. This repartition aims at reducing hardware and access concurrency requirements for instrument services and assumes that the digital models involved in the CaaS system are evaluable independently of the respective physical instruments. This allows the exploitation of cloud computing and on-demand hardware-scalability,

[2] Time-synchronization is considered most critical for consistent metadata when collaboratively using multiple instruments. Systematic delays between physical measurement and software timestamps should be compensated if possible.

e.g. evaluating computationally intensive instrument models ($\mathbb{M}$) based on ray tracing or complex planning algorithms ($\mathbb{P}$). For database-driven microservices (e.g. $\mathbb{E}$, $\mathbb{P}$ and $\mathbb{U}$), cloud-based platforms have emerged to a popular infrastructure in other service-oriented domains already. Hence, concepts for high availability, scalability and resilience respectively redundancy exist and can be utilized when implementing a CaaS system [MORE18].

Consumers constitute the top layer of the architecture with individual hardware determined by the respective application, which can reach from user interfaces on consumer devices over cross-company data exchange platforms to robotic actor control. Their scalability and resilience can only be provided by CaaS to the extent that their interaction with the service is not a major bottleneck, which is a result of the underlying layers' performance. A second architectural aspect from a consumer's perspective is the network performance when interacting with the instrument: The delivery of a measured position with minimal latency and jitter and maximum reliability can be decisive for closed control-loops. This necessity is not only raised from the physical side, but also reflected on the network's side in IEEE's *Time-Sensitive Networking* standards [LOBE19] and 5G's aims to provide ultra-reliable low-latency communication [SACH18]. Therefore a data flow is not only foreseen between adjacent layers, but also directly between consumer and instrument service or, after negotiation via the instrument service, the instrument-specific layer[3].

Figure 5.2 shows the envisaged communication flow of a consumer with the different layers. It initiates by stating the requirements and allocating an entity as discussed later in Chapter 6. Only thereafter the consumer interacts directly with the service encapsulation of the instrument as required for the operation, while the latter (optionally) authenticates the consumer and verifies its allocation and at the same time forwards non time-critical interaction to the instrument-specific layer. Through the instrument service or the respective protocol used, a direct communication from instrument to consumer largely independent of the overall system can be negotiated. As side-effects, among others, this enables the definition of *Quality of Service (QoS)* metrics for position information streams and the application of in-network processing techniques [GLEB19]. Semantically, the proposed architecture resembles the designs presented in Section 2.2 and found in literature [ALFU15, p. 2349], indicating that according platforms may be used when implementing a CaaS system. On the other hand, it must be stated that this proposition is non-exclusive and other approaches may lead to an adequate implementation of CaaS as well. Consequently, the CaaS prototype developed in Chapter 7, which follows the four-layer structure, only represents a non-exclusive validation[4].

[3] An example is the ability of an instrument to publish a subset of its data over a dedicated real-time network interface, e.g. as available for the Leica AT960™ laser tracker as additional feature pack. It is expected that the currently only sporadic availability of such a function increases with 5G's ultra-reliable low-latency communication efforts.

[4] During one of the initial design cycles, a three layer architecture was evaluated as well.

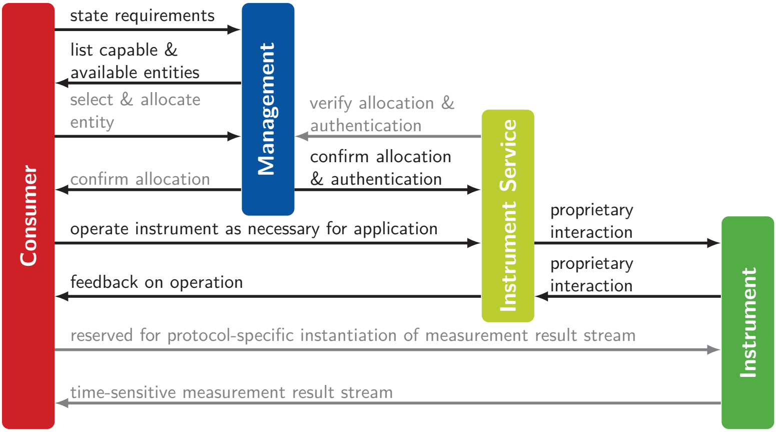

Figure 5.2: Expected interaction order with the individual layers (cf. Figure 5.1) of the CaaS system from a consumer initiated perspective. The time-sensitive track is reserved for future use cases when technologies such as standardized ultra-low latency communication or in-network processing have established themselves. The instrument microservice is expected to coordinate the provenance of a time-sensitive data stream from the instrument. The verification of allocations initiated by an instrument service is an optional step and only required in networks where malicious consumers may be expected.

5.4 Intermediate Summary

A decomposition of a CaaS into microservices has been carried out as the latter have been identified beneficial for flexibility in terms of system decomposition, design and implementation. Based on their individual characteristics, a repartition among four layers with explicit hardware propositions involving edge and cloud computing as well as an envisaged communication flow has been elaborated. In conjunction with the given flexibility, the existence of appropriate hardware and network infrastructures to implement CaaS systems is assumed. This assumption is reinforced by the coherence between the proposed four-layer architecture and the *Internet of Production* framework (cf. Figure 2.4). Scalability and resilience have been considered to avoid that CaaS becomes a consumer's bottleneck and to provide high availability of the virtual metrological reference frame. Moreover, the eventually direct communication between consumer and instrument service facilitates the achievement of low latencies required in the domain of automation.

Does an appropriate system architecture respecting interfaces and decomposition to implement and servitize a virtual, metrology-based reference frame exist? – Anticipating the successful creation of a CaaS artifact in the relevance cycle described in Chapter 7, the third research question is affirmed.

6 Management of Individual LSM Instruments as Service Resources

This chapter is dedicated to the fourth research question which aims at investigating the management of the Large-Scale Metrology instruments respective their mobile entities as resources of CaaS. Seeking analogies in load balancing for scalability and resilience in cloud computing, the following subtasks are listed by AFZAL et al.: The identification of a service user's task requirements, the identification of available resources and their details, scheduling of tasks and allocation of resources and the migration of tasks in case of resource exhaustion [AFZA19]. Basing on this classification, task requirements and resource details are described by a set of metrological characteristics of a mobile entity over a defined time span in Section 6.1. The entity-centric view emanating in Chapter 4 is maintained as it covers consistency among resource management and interfacing, technological abstraction and multi-entity instruments. Subsequently the relation to manufacturing respectively assembly planning, required due to the expected integration of CaaS into a superordinate production system, is demarcated in Section 6.2. Finally, scheduling and allocation of entities are discussed in Section 6.3 exploring a green-field mathematical approach. Figure 6.1 provides an overview of how the microservices dissected in the previous chapter are related to each other in the process of resource allocation such that interfaces between recommendation of available entities, a choice of entity by the consumer and its definitive allocation prevail.

The systematic, model-based selection of Large-Scale Metrology instruments for measurement and assembly tasks has been previously studied in literature, e.g. by MAROPOULOS et al. within the concept of *Metrology Process Models* and ZHAO et al. in a measurement process interface analysis [MARO08, ZHAO11]. NICKSCH et al. define a set of 10 capabilities to assess the capabilities of Large-Scale Metrology Instruments specific to factory and station requirements in flexible automation systems in a weighted scoring scheme based on expert knowledge [NICK20]. The approach elaborated here differs from these by introducing the opportunity for complex, opaque uncertainty models, a notion of resource management where the entirety of tasks is not known in advance and the simultaneous possibility to include externally determined allocation decisions.

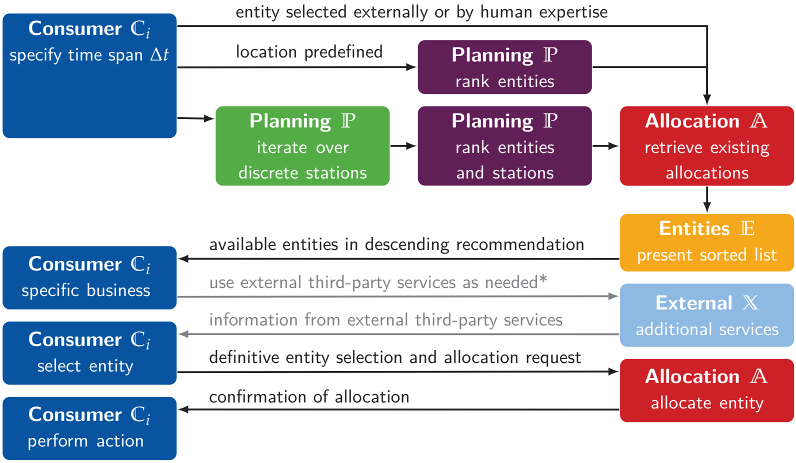

Figure 6.1: Order of subprocesses and corresponding microservices in entity assignment. The involvement of $\mathbb{P}$ depends on whether the consumer predefines a specific mobile entity or location for the action. The use of external services $\mathbb{X}$ ($*$) must be initiated from the consumer's side to maintain the ability of CaaS to integrate into a priori unknown applications. The final step of entity selection and allocation request can technically be based on arbitrary rationale of the consumer. The time span Δt refers to the total time the consumer requires physical access to the mobile entity, i.e. including specific initialization time.

6.1 Determination of Relevant Properties of Large-Scale Metrology Instruments

Most model-based instrument selection approaches have an assessment of technical, economic and ergonomic features in common, which is described by FRANCESCHINI et al. independent of a resource allocation framework [FRAN14a]. Table 6.2 summarizes the relevant properties identified as intersection of the referenced literature briefly summarized in Table 6.1, knowledge base and insights evolved during the implementation of the applications described in Chapter 7. Consistent with the unified entity-centric view of CaaS, the properties are expressed on mobile entity level and, if position-dependent, transformable to the global coordinate system Σ_0. Moreover, the characteristics are evaluated with respect to the current configurations of the individual instruments, i.e. layout optimizations as proposed by MAROPOULOS et al. and CHEN et al. are interpreted as independent question[1] [CHEN17, MARO08].

[1]The identified properties can vary in the time domain without significantly changing the microservice interfaces and thereby be connected to an additional microservice performing layout configurations.

	CAI et al. *Benchmarking, 1...10*	**MUELANER et al.** *Quantitative*	**MAROPOULOS et al.** *Qualitative*	**FRANCESCHINI et al.** *Qualitative*	**NICKSCH et al.** *Benchmarking, 0...9*
working volume, scale, size, envelope, scalability	✓	✓	✓	✓	✓
target material, part interface, work piece restrictions, adaptorless measurement, contact/non-contact, method	✓	✓	✓	✓	✓
environmental conditions, topology	✓	✓	✓	✓	✗
scalar uncertainty, accuracy capability, metrological performance	✓	✓	✓	✓	✓
cost (utilization, deployment, operation, instrument)	✓	✓	✓	✓	✗
technological readiness, technological obsolescence	✓	✗	✗	✓	✗
concurrency (number of targets), simultaneous	✗	✓	✗	✗	✓
degrees of freedom	✗	✓	✗	✗	✓
measurement frequency	✗	✓	✗	✗	✗
speed, dynamics	✗	✗	✓	✗	✓
SA compatibility, supported software	✗	✓	✗	✓	✗
setup time, configuration effort	✗	✓	✗	✓	✓
ergonomics, maintainability	✗	✗	✗	✓	✓

Table 6.1: Comparison of different Large-Scale Metrology instrument capability models found in literature [CAIB10, MUEL10, MARO08, FRAN14a, NICK20]. Different namings have been grouped appropriately. MAROPOULOS et al. and FRANCESCHNI et al. describe capabilities on a general qualitative level. CAI et al. and NICKSCH et al. aim at introducing a normalized benchmarking scheme to apply objective selection algorithms. MUELANER et al. attribute physical quantities to the capabilities intended for a software-based representation and use. In all representations, uncertainty contribution and working volume are not considered as complex functions leveraging a physically motivated instrument model.

A discriminating prerequisite is the operating respectively visibility range of the instrument regarding the entity in question, which must include the positions to be measured anticipated by the consumer. While this is commonly expressed in local volumetric shapes [QIF03, pp. 403-404] or scalar sizes [FRAN14a, MUEL10], CaaS formulates this problem as Boolean response function to an anticipated position in global coordinates, allowing to consistently interchange or extend this function with more complex models. Additionally, an angular acceptance function is analogously introduced to conceptually account for scenarios where the change in orientation of a target (e.g. a standard corner cube reflector) is limited.

The second essential metric is the expected measurement uncertainty contribution, which influences the entity selection by uncertainty requirements defined and deduced from the underlying process by the consumer itself (cf. Section 6.2). As there are numerous possibilities to predict the uncertainty contribution of an instrument, a function operating in local coordinates and returning a covariance matrix[2] in response to a provided position and velocity vector is chosen. The anticipated velocity is considered as optional, which may not be used by the underlying uncertainty model. Its implementation can, among others, be based on theoretical models [HUGH11, GALE15], empirical data [QUIN18] or Monte Carlo simulation [GALE16] and, as discussed in Section 5.2, technically deferred to a distinct provider of the model. The transformation to global coordinates is performed in an additional step, its systematic contribution to the combined covariance (cf. eq. (3.9)) is therefore added as separate characteristic. It is expected that the instrument models are independent of the instrument's integration into a CaaS system, therefore a greater model autonomy is maintained by this choice.

For dynamic applications and their associated control loops, estimates of the time the physical measurement requires (e.g. related to camera exposure), the dead time (e.g. due to data processing) to the delivery of the value, the maximum sample frequency and the upper limit of velocity allowed during operation may be of interest as selection criteria and included as scalar values to summarize dynamic capabilities as required by existing perspectives to Global Reference Systems [NICK20]. This poses an extension to the scope of metrology process models mainly focussing on static GD&T related use cases. From a traditional point of view for the latter, climatization and traceability are of mandatory importance. With emerging portable and shop floor use oriented instruments (cf. section 2.1) and cooperative scenarios with less strict, non-traceable requirements, the limits of temperature, pressure and humidity within which the stated covariance can be achieved and a flag whether traceability is provided, are chosen as properties.

While the interface model introduced in Chapter 4 does functionally not include probes, the possible interaction with the measurement object is a relevant criterion [MUEL10, pp. 3-4]. The approach presented in Table 6.2 accounts for five different

[2] The representation as covariance matrix is chosen as it corresponds to the uncertainty representation discussed in Chapter 3 and allows identical execution of data processing algorithms.

types of targets: interfaceable reflectors (e.g. SMRs), passive markers (e.g. for photogrammetry), natural features (targetless, e.g. laser radar), movable touch probes (e.g. CMM probes) and complex targets (e.g. iGPS™ PCEs). The target type is complemented by indications whether the entity can be attached to moving objects or is actually tied to a kinematic, whether it provides simultaneous orientation measurements and if it is effectively measuring point clouds respectively scanning a surface. Orientation measurements are regarded as convenience function and not as primary part of a coordinate measurement. It may be achieved by combining coordinate measurements of multiple subtargets but can also be obtained by means of other principles, e.g. IMUs. Overall, it is assumed that the chosen set of descriptors may fail in singular cases. To avoid further increasing the complexity of criteria, it is foreseen that expert knowledge can replace the instrument selection process from the consumer side by explicitly requiring one or more specific entities[3]. For such and similar cases of instrument selection deferral, a flag whether the entity requires exclusive, non-simultaneous use of the instrument is included.

CAI et al. deduce a detailed description of costs related with the acquisition, setup and deployment of measurement instruments [CAIB10, pp. 439-440]. As CaaS assumes that acquisition and setup have been carried out before the instrument enters the system as a resource, only the variable cost over time, i.e. related to necessary human resources, consumables or pay-per-use business models is included. Any software interoperability considerations as included by FRANCHESCHINI et al. are omitted due to the service oriented design and unified interface established in Chapter 4, as are any ease-of-use or technological readiness metrics [FRAN14a]. The physical interface of a mobile entity is considered to the extent that an interface with a defined, if appropriate calibrated, offset to the position information delivered exists. The physical integration itself is assumed as responsibility of the consuming application.

Figure 6.2 shows how the properties of an entity are practically deduced for a consumer seeking a list of available entities: For entity management ($\mathbb{E}$) most characteristics can be deduced from the model of the entire instrument based on their physical behavior. For different entity types specific modifications respectively extensions are expected, e.g. adapted target-related uncertainty contributions for different reflecting targets of a laser tracker. With the models operating in local coordinate systems agnostic of their use in a CaaS setup, position-dependent characteristics are transformed to Σ_0. These are complemented by any information inferred from microservices representing external constraints ($\mathbb{X}$) and the existing allocations ($\mathbb{A}$) by other consumers or previous requests. Furthermore, a single physical entity may be a functional entity of multiple instruments, e.g. an SMR shared by multiple laser trackers. As consequently its model-based characteristics vary, it is expected to occur multiple times in the inventory of $\mathbb{E}$. To correctly reflect the repeated occurrence and related availability in $\mathbb{A}$, a list of physically identical entities, further denoted as siblings, shall be maintained.

[3] This is a main aspect for separating the allocation and planning microservices $\mathbb{A}$ and $\mathbb{P}$ in Section 5.2.

Characteristic	Symbol	Description
Position Coverage	$\mathcal{B}(\hat{\boldsymbol{p}})$	Boolean response function whether a mobile entity is able to measure at $\hat{\boldsymbol{p}}$.
Angular Acceptance	$\mathcal{Q}(\hat{\boldsymbol{p}}, \hat{\boldsymbol{n}})$	Boolean response function whether at $\hat{\boldsymbol{p}}$ the target is able to measure at an orientation expressed as normal vector $\hat{\boldsymbol{n}}$, e.g. for scenarios with rotating end effectors.
Covariance Prediction	$\hat{\mathbf{V}}(\hat{\boldsymbol{p}}, \hat{\boldsymbol{q}})$	Prediction of the covariance matrix at $\hat{\boldsymbol{p}}$, e.g. model-based. The anticipated velocity $\hat{\boldsymbol{q}}$ is designated for uncertainty models reproducing dynamic characteristics.
Transformation Covariance	$\hat{\mathbf{S}}(\hat{\boldsymbol{p}})$	Estimated covariance contribution due to the transformation to global coordinates at $\hat{\boldsymbol{p}}$ (cf. eq. (3.8)).
Measurement Time	$t_{measure}$	Time required per measurement, e.g. for estimating uncertainty induced by motion.
Dead Time	t_{dead}	Estimated time between physical measurement and its delivery via the interface.
Sample Frequency	f_{sample}	Maximum possible frequency for measurements, including dead times, e.g. for designing control loops.
Maximum Target Velocity	v_{max}	Maximum velocity the target is allowed to move while measuring.
Environmental Limits	$\{T_{min}, T_{max}\}$ $\{p_{min}, p_{max}\}$ $\{H_{min}, H_{max}\}$	Limits for temperature (T), pressure (p) and humidity (H) allowed during correct operation.
Orientation Measurement	$\mathcal{O}$	Boolean indication whether the orientation of the mobile entity is captured.
Target Type	$\mathcal{F}$	Type of the mobile entity as one of {reflector, marker, natural feature, probe, complex}.
Exclusiveness	$\mathcal{R}$	Boolean indication whether using the target disables other targets of the system (e.g. for a laser tracker).
Traceability	$\mathcal{T}$	Boolean indication whether the position information is traceable.
Mobility	$\mathcal{K}$	Boolean indication whether the entity can be attached to a moving unit or is moved by a fixed kinematic (e.g. CMM).
Scanning	$\mathcal{Z}$	Boolean indication whether the entity is representative for a point cloud measurement (e.g. laser radar).
Cost Factor	$\frac{\partial C}{\partial t}$	Additional variable cost per time for using the target/instrument.

Table 6.2: Properties of a position measuring entity relevant to process planning. It is assumed that characteristics that are depending on the actual position can be evaluated through a model and per anticipated location.

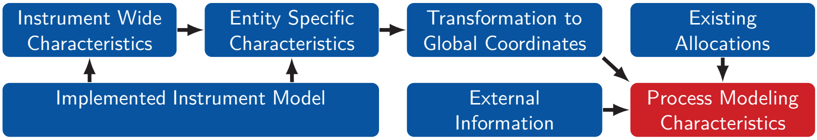

Figure 6.2: Development of characteristics used to interface with process planning for choosing an appropriate instrument and entity starting from an implemented instrument model. The data flow is bidirectional regarding the evaluation of instrument models in their local coordinate systems for queries in global coordinates. External information refers to custom modeling characteristic obtained from external microservices, e.g. CAD based visibility analyses.

For practical realizations it should be noted that CaaS solely defines the interface to instrument/entity models and characteristics and not their implementations, which can be in simplified or trivial form (e.g. empirical estimations interpolated over a grid or constant values) for fast service ramp-up and then seamlessly refined. Moreover, without modifying infrastructure or interaction patterns, the approach can be extended with additional criteria.

6.2 Demarcation of Consumer Requirements from Process Planning

To determine the mobile entities suited as resource to offer the service to a consumer, a set of requirements corresponding to the properties developed in the previous section must be established. Given the wide range of different and potentially unknown applications incorporating Large-Scale Metrology and their unique complexity, a concise service definition and implementation is only possible if this set of requirements is defined by the consuming party. This action typically involves the following steps [Maro08, p. 478]:

(1) Predict the measurement positions leveraging a digital process model, thereby implicitly obtaining the spanned volume. For processes with very dense point clouds a subset may be used assuming little local variation of entity properties.

(2) Deduce measurement uncertainty limits from geometric process or product tolerance specifications, either using statistical measures such as process capability indices or Monte Carlo based simulations.

(3) Determine the possible interaction with the object considering working part and surface restrictions.

(4) Obtain additional metrological characteristics needed (cf. Table 6.2) from the process model or state their irrelevance.

The procedure can be illustrated taking the straight-forward example of examining a circular feature with $T = \pm 500$ µm specified tolerance. Implying a requirement of $Q_{MP} \leq 15\%$ with $Q_{MP} = 2U_{MP}/T$ as defined in VDA 5 respectively ISO/CD 22514-7 [DIET11], one obtains a maximum permissible uncertainty of $U_{MP} = 1.96 \cdot \sigma_{diameter,max} = 37.5$ µm. Allocating a normally distributed half share of the uncertainty budget to other influences, 13.6 µm remain for the actual coordinate measurement process. Presupposing a strategy of $n_{points} = 16$ probing points equally distributed on the circumference, the uncertainty propagation for an evaluation following HERNLA can be inverted to deduce an upper uncertainty limit of $\sigma_{point,max} = 24.2$ µm [HERN16]. Aiming at using a single entity, the contribution of the transformation to global coordinates ($\hat{\mathbf{S}}$) does not enter the uncertainty budget such that $\hat{v}$ as defined in eq. (3.10) holds to classify whether the covariance restrictions are met. Dynamic parameters ($t_{measure}$, t_{dead}, f_{sample}, v_{max}) and orientation ($\mathcal{Q}$, $\mathcal{O}$) are also not discriminating, in contrast to traceability ($\mathcal{T}$) and a probing target type ($\mathcal{F}$), which are mandatory. Variable cost and exclusiveness ($\mathcal{R}$) are neglected in this example as they are only relevant in a more elaborated economic context. The required environmental limits must match with the conditions that can be satisfied within $\mathcal{S}$ or compared to live data.

Allowing both portable, light-based systems (e.g. laser tracker referenced, handheld probes) as well as rigid kinematics to perform the task, the mobility flag ($\mathcal{K}$) can be left open. While the position of the measurement points relative to the part is trivial due to the circumferent strategy, the example illustrates that the question of where within the shopfloor volume $\mathcal{S}$ covered by CaaS the action shall be carried out is more complex: One could either assume the location is predefined by the overall process sequence and the respective location of pre- and proceeding resources or interpret the task of finding a suitable location where one or more entities presenting the required characteristics can operate as part of CaaS. This is resolved by separating the microservices $\mathbb{E}$, $\mathbb{P}$ and $\mathbb{A}$ as discussed in Section 5.2, where $\mathbb{E}$ presents an identical interface to a consumer predefining the location or utilizing its planning algorithm as well as to $\mathbb{P}$, the internal planning microservice further discussed in the upcoming section. For $\mathbb{A}$, the decision basis for the allocation demand is irrelevant such that a consumer can implement arbitrary logics.

Linking CaaS to its application in a metrology-assisted assembly scenario, the individual entities can be seen as assembly resources. GRUNERT et al. discuss different service-oriented information modeling possibilities, concluding with an own approach based on the categories of capabilities, setup units and status [GRUN19]. Capabilities are represented as a collection of parameters expressable as scalar values or one-dimensional ranges. Therefore the characteristics listed in Table 6.2 can be transformed to this view using one-sided open intervals where appropriate. The cost factor translates to a cost axis as defined by the authors. The status can be matched with existing allocations of an entity in $\mathbb{A}$, while the setup units do not have a direct correspondence in the current CaaS concept. BUCKHORST et. al explicitly name metrology systems as resources linked to stations within the concept of Line-less Mobile Assembly Systems (LMAS). The presented operations planning method presupposes that a boolean relation between process requirements and station capabilities exists [BUCK19]. This can directly be achieved within CaaS leveraging the established characteristics for a given position of the respective station.

6.3 Entity Choice and Allocation based on Novel Metric

Allocating an entity for a task after a successful match of the characteristics developed in section 6.1 inhibits its further use, or, in case of non-simultaneous technologies, also the use of all other entities belonging to the respective instrument. In a scenario with multiple CaaS consumers acting in parallel, resolving the degrees of freedom regarding the choices of entity, allocation time and task subvolume have substantial impact on the overall efficiency of the system. Reutilizing the previous example of measuring a circular feature, assume an articulated arm and a laser tracker referenced handheld probe are entities matching the required characteristics: Allocating the laser tracker, which typically operates in a significantly larger subvolume of $\mathcal{S}$, blocks all its other entities and, compared to the choice of the articulated arm, thereby leads to an increased probability that requests by other consumers for the same period of time cannot be satisfied.

On the other hand, a correct cost-based decision is only possible if the impact of all other effects, e.g. increased transport efforts or idle times can be evaluated. This would imply the existence of a shop floor-wide planning system including a global optimization objective, which would have to incorporate a significant level of complexity. Such systems are subject to current research [BUCK19]. Moreover, a major intended benefit of service-orientated approaches is to encapsulate as much of the complexity and domain particularities as possible. An approach to accommodate both scenarios is to enable the planning microservice $\mathbb{P}$ to recommend the choice of an entity to a consumer based on an internal ranking function. Hereby a procedure similar to CASSARAM by PERERA et al. shown earlier in Figure 2.6 is followed.

The assignment of metrology systems to measurement tasks has previously been discussed by CAI et al. expressing the capability of an instrument with regard to a demanded characteristic in normalized integer ranges from 1 to 10 as summarized earlier in Table 6.1 to form a matrix representation of concurrent tasks and apply weighted zero-one goal programming [CAIB10, pp. 441-442]. While an equivalent mapping of the characteristics stated in Table 6.2 may be possible, this approach assumes that all concurrent tasks are known prior to the concrete assignment, which, if presupposed in a service-oriented scenario, leads to necessary temporal synchronization among the requests of the service consumers and in turn requires planning on a global level. To avoid the latter dependency, the internal planning algorithm must be able to meaningfully react to entity requests by decoupled consumers and thereby effectively assume that an arbitrary set of characteristics can be requested by any party at any time in future.

In terms of service-oriented architectures, this question corresponds to maintaining service availability and load-balancing, which are common problems in distributed computing systems [AFZA19, SHAH17]. However, due to the heterogeneity and locality of the resources in form of LSM instruments, existing approaches are difficult to transfer. Therefore a novel, green-field approach[4] introducing a phase-space like metric Ω is explored under the hypothesis that maximizing an appropriate phase-space is able to represent the service availability objective. The operator $\hat{H}$ defined in eq. (6.1) returns the lowest uncertainty contribution[5] that can be achieved for a provided position $\hat{\boldsymbol{p}}$ and velocity $\hat{\boldsymbol{q}}$ over a time span Δt. It is then applied in eq. (6.2) to define the integration boundary depending on an upper uncertainty limit U, while p_0 and q_0 are normalization constants[6]. Figures 6.3 and 6.4 show a color-coded representations of $\hat{H}$ for a virtual shop floor setup using the models further introduced in Section 7.2.

$$\hat{H}\left(\hat{\boldsymbol{p}},\hat{\boldsymbol{q}},\Delta t\right) = \min_{\substack{\mathcal{E} \text{ available in } \Delta t \\ \text{and } \mathcal{B}(\hat{\boldsymbol{p}}) = \text{true}}} \operatorname{Tr} \hat{\mathbf{V}}\left(\hat{\boldsymbol{p}},\hat{\boldsymbol{q}}\right) \tag{6.1}$$

$$\Omega\left(U,\Delta t\right) = \frac{1}{p_0^3 \cdot q_0^3} \cdot \int\limits_{\hat{H}(\hat{\boldsymbol{p}},\hat{\boldsymbol{q}},\Delta t) \leq U} \mathrm{d}^3\hat{\boldsymbol{p}}\, \mathrm{d}^3\hat{\boldsymbol{q}} \tag{6.2}$$

As such, Ω is monotonically increasing with respect to the available entities[7] and U. This allows the definition of Γ as metric on an integral basis in eq. (6.3). Within Γ, an entity $\mathcal{E}$ effectively obtains more weight by either allowing a low uncertainty contribution or a large operating subvolume, while the exponential integration allows for a linear match between the uncertainty's order of magnitude and phase space with weighting coefficient α. The function γ is introduced to allow user-specific weighting modifications and can be constant in its most trivial realization.

[4]The approach has been inspired by the phase space definition for micro-canonical ensembles in statistical physics.

[5]The trace of the covariance matrix is used as representative uncertainty parameter as motivated for eqs. (3.10) and (3.11).

[6]Visually speaking, at constant velocity Ω corresponds to the volume on the shop floor where coordinate measurements are possible with uncertainty lower than U.

[7]This implies the assumption that the presence of one entity has no influence on the uncertainty of another one and therefore cannot deteriorate $\hat{H}$.

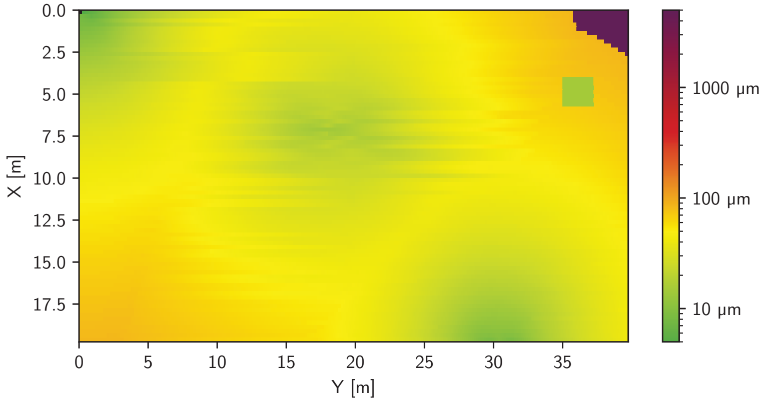

Figure 6.3: Color-coded top view representation of $\hat{H}$ for a virtual shop floor setup consisting of 3 laser trackers, an indoor GPS system with 6 transmitters, an ultrawideband system and calibrated machine tool. Depending on the uncertainty requirements of the application, the volume available is limited to certain regions, hence the phase space analogy. The volume covered by the machine tool appears as isolated rectangle. Details on the simulation setup are summarized in Appendix E.

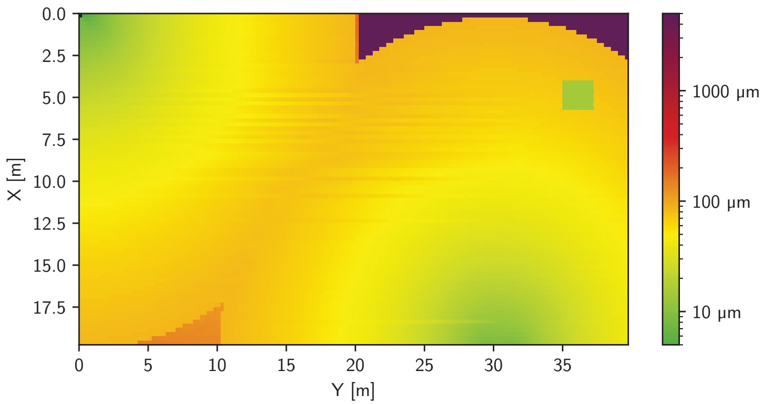

Figure 6.4: Color-coded representation of $\hat{H}$ for the same setup as in Figure 6.3 but with the central laser tracker being considered unavailable. In direct comparison, the possible volume for applications with low uncertainty is reduced and the operation range of the remaining laser trackers is clearly visible.

Considering the simple example of $U_{max} = U_0 = 1\,\mathrm{m}$, $\alpha = \ln(10)$, $\gamma = 1$ and static uncertainty models, a volume where $U \leq 100\,\mu\mathrm{m}$ can be achieved is entering Γ with twice the weight compared to a volume where only $U \leq 1\,\mathrm{cm}$ is possible.

$$\Gamma(\Delta t) = \int_{-\infty}^{\ln\left(\frac{U_{max}}{U_0}\right)} \Omega\left(U_0 \cdot \mathrm{e}^{\alpha\cdot\tau}, \Delta t\right) \cdot \gamma\left(U_0, \alpha, \tau\right) \mathrm{d}\tau \tag{6.3}$$

$$\Delta\Gamma(\Delta t) = \Gamma(\Delta t) - \underbrace{\Gamma'(\Delta t)}_{\Gamma(\Delta t)\text{ excluding }\mathcal{E}'} \geq 0 \tag{6.4}$$

$$\Gamma_{\mathcal{E}'}(\Delta t) = \Gamma(\Delta t)\Big|_{\hat{H}\text{ over solely }\mathcal{E}'} \tag{6.5}$$

Allocating an entity $\mathcal{E}'$ has a monotonically decreasing effect on Γ for subsequent evaluations, with zero difference if other unallocated entities with identical uncertainty model and coverage exist which are able to operate simultaneously (e.g. iGPS™ PCEs). In reverse, if a consumer request can be satisfied by multiple entities, the one leading to the smallest decrease $\Delta\Gamma$ as defined in eq. (6.4) should be recommended. In the case of an equal result (e.g. because an entity with smaller uncertainty contribution is available over the whole volume considered), the metric $\Gamma_{\mathcal{E}'}$ defined in eq. (6.5) to represent the maximum phase-space contribution of an individual entity should be used as auxiliary minimal criterion.

As no immediate reference algorithm for entity scheduling is available, the chosen explorative approach is investigated on a simulation basis in comparison to randomized[8] assignment. In both cases, an upper limit to the trace of the expected covariance is imposed as discriminating criterion without further constraining entity properties. Figure 6.5 shows the results of a simulated situation involving virtual instruments as described in Appendix E representing three laser trackers (4 entities each, exclusive), an indoor GPS system (6 entities, non-exclusive), an ultra-wideband system (4 entities, non-exclusive) and one fixed kinematic (1 entity). For the simulation study summarized in Appendix F, in 43 out of 100 series the Γ-sustained entity choice outperformed the random approach and the opposite case is observed in 1 out of 100 series. For 56 series, the result is indistinctive. For the parameters of the ranking function, $U_{max} = U_0 = 1\,\mathrm{m}$, $\alpha = \ln(10)$ and $\gamma = 1$ were used. For the case that a request cannot be satisfied at all, it is ignored in the comparison of the algorithms' performance. Thereby a major issue of the ranking algorithm is exposed: If the coverage redundancy by different instruments is low and the entity choice potentially narrowed by additional constraints following Table 6.2, ranking becomes irrelevant.

[8] The comparison against a round-robin approach is omitted as it would be severely biased by the simulation design and its internal order of available instruments.

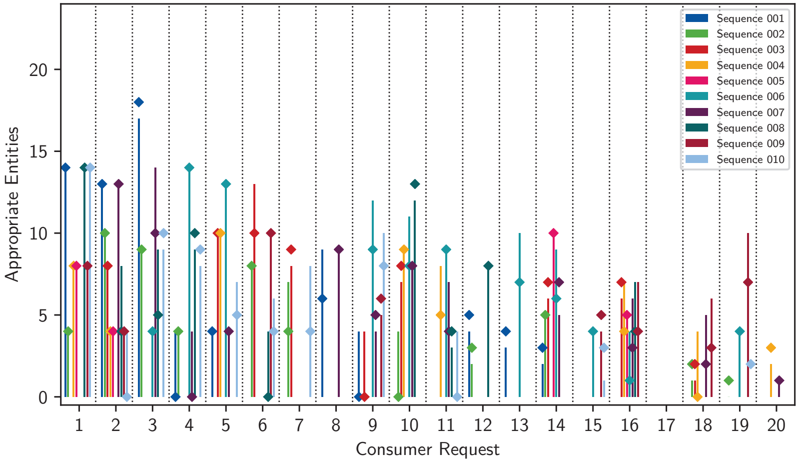

Figure 6.5: Number of appropriate entities for a sequence of requests with randomized upper uncertainty limit and working volume on a virtual shop floor. The solid bars represent the Γ-sustained entity choice, while the diamond markers refer to random allocation. The former slightly outperforms the latter until saturation effects arise. With random allocation, the situation where no entity is available to fulfill the request respectively provide the service may occur earlier. Details of this study are summarized in Appendix F

On the other hand, the developed metric follows a mathematically motivated deduction and can be linked to the earlier mentioned concept of Line-less Mobile Assembly Systems taking into account station-based operations planning. Figure 1.1 depicts the dissection of the shop floor into stations containing a confined workspace in which metrology systems are expected as resource. The effective discretization greatly reduces heuristic search complexity for scenarios where a consumer does not predefine the location of the task as the individual stations can be queried iteratively. Figure 6.6 depicts the problem on a schematic basis. Eqs. (6.6) and (6.7) define the discretized equivalents $\hat{H}^*$ and Ω^* to eqs. (6.1) and (6.2). Moreover, the characteristic velocity $\hat{\boldsymbol{q}}^*$ is introduced to eliminate the continuous velocity phase space variable[9].

$$\hat{H}^*\left(\mathcal{A},\Delta t\right) = \max_{\hat{\boldsymbol{p}}\in\mathcal{A}} \hat{H}\left(\hat{\boldsymbol{p}},\hat{\boldsymbol{q}}^*,\Delta t\right) \tag{6.6}$$

$$\Omega^*\left(U,\Delta t\right) = \sum_{r,s=1}^{m,n} \begin{cases} \frac{1}{p_0^3}\cdot\int\limits_{\mathcal{A}_{r,s}} \mathrm{d}^3\hat{\boldsymbol{p}} & \text{if } \hat{H}^*\left(\mathcal{A}_{r,s},\Delta t\right)\leq U \\ 0 & \text{else} \end{cases} \tag{6.7}$$

[9]The velocity does not have a significant contribution to the phase space as long as instrument and the respective uncertainty models do not include its dependency. It can be reincluded without limitation by modifying the integral in eq. (6.3).

With appropriate normalization p_0, Ω^* represents the number of stations where an entity contributing with a total uncertainty below U within the entire station's volume is available. Deducing Γ^* in analogy to Γ in eq. (6.3), the proposed ranking approach can be extended by a station dimension with the underlying objective to maintain the highest number of stations with the lowest uncertainty contribution possible. While a discretization in equally sized cells represents an intuitive approach, both LMAS and the developed methodology are also applicable with irregular discretization[10].

In all cases, a singular cost estimation for entity use can be calculated from the product $\frac{\partial C}{\partial t} \cdot \Delta t$ which may be used as additional metric by a consumer to chose an entity. Nevertheless, this point of view is very limited as it may not be able to cover costs occurring in a superordinate scope due to delays or relocations in other processes caused by local and/or temporal service unavailability with appropriate metrological characteristics. Unforeseeable knock-on effects, opaqueness of consumers to CaaS and the opportunity for knowledge-based entity choice motivate the decision taken not to include any reallocation[11] procedure internal to CaaS as this may lead to an implicit interdependence between otherwise unrelated processes. By including the ability to retract an allocation, jointly organized consumers are still able to implement reallocation logics themselves.

Inversely, the frequency of service unavailability can be used as an indicator for orchestration strategies. The same holds for the metrics Γ and Γ^*: By evaluating their increase, the potential effect of enhancing the CaaS system's resources with an additional instrument can be assessed. The requirements and process to do so contains the following steps:

(1) Ensure an according instrument microservice with appropriate communication protocol is available or implement the latter if required and connect the respective edge device to the present IT infrastructure.

(2) Physically integrate and put into operation the instrument on the shop floor and determine its coordinate transformation to Σ_0 using one of the methods presented in Chapter 3.

(3) Identify or, if applicable, implement and adapt the mathematical models required to evaluate the characteristics of the mobile entities introduced in Section 6.1.

(4) Register the novel instrument and its entities in $\mathbb{E}$ to enable planning, selection and allocation.

[10] For instance, a cell containing a machine tool should be modeled by its working volume.

[11] Reallocation refers to redirecting a consumer to another mobile entity, subvolume or time span after its allocation has previously been confirmed.

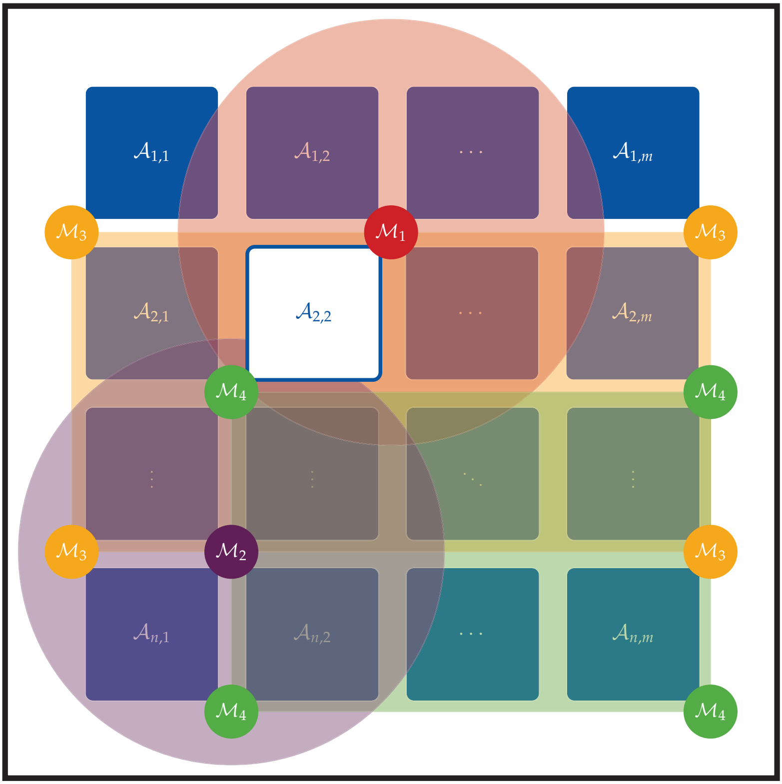

Figure 6.6: Schematic representation of a scenario for station-based, covariance determined resource allocation. Let $\mathcal{M}_1$ and $\mathcal{M}_2$ be two instruments that cannot measure multiple entities simultaneously, and $\mathcal{M}_3$ and $\mathcal{M}_4$ able to do so with expected covariance contributions (cf. eq. (3.10) and Table 6.2) $\hat{v}_{0,1} < \hat{v}_{0,2} < \hat{v}_{0,3} < \hat{v}_{0,4}$. If an application requires $\hat{v}_{0,1}$, choosing $\mathcal{A}_{1,2}$ over $\mathcal{A}_{2,2}$ leaves more cells available for other applications for which $\hat{v}_{0,3}$ is sufficient. For the case $\mathcal{A}_{2,2}$ is predetermined due to other constraints and $\hat{v}_{0,3}$ is sufficient, choosing an entity of $\mathcal{M}_3$ maintains the availability of M_1 for other cells (e.g. $\mathcal{A}_{1,2}$).

6.4 Intermediate Summary

Can the individual, technologically heterogeneous instruments be managed as service resources without interacting with superordinate planning from an industrial application's perspective? – An abstracting set of metrological characteristics taking into account existing approaches in literature has been established to allow mapping between tasks and resources on mobile entity level. However, the interdependency with superordinate systems cannot be completely resolved if global optimization objectives exceeding the scope of CaaS are pursued. A compromise has been elaborated by enabling planning microservice in CaaS to present a ranked list to a resource-inquiring consumer. For this purpose, a novel phase-space like ranking metric has been deduced and positively investigated on a simulation basis, nevertheless further research particularly containing evaluations on more complex scenarios is still required to substantially assess its benefit for scheduling and orchestration purposes. Moreover, the results of hitherto performed simulations suggest that the importance of resource management greatly depends on the prevalence of mobile entities with redundant characteristics and a substantial number of competing consumers, such that an evaluation without specific use-case is regarded as difficult and biased. To maintain a great degree of flexibility, the relation between resource choice, planning and allocation management has been designed with clear interface to facilitate the adaption of a CaaS system's resource management. Thereby the ability to incorporate external decision making, e.g. based on expert knowledge or historical data is explicitly maintained. Separately, a fully interchangeable use from a consumer's perspective would require the engineering of a modular system for physical interfacing with remaining uncertainty whether all potential use cases, which may be unknown to the service by design, would be appropriately covered. Eventually, the fourth research objective can be partially affirmed in the sense that a technical proposition to decouple resource management from superordinate planning has been made, while a comprehensive assessment of its beneficial applicability in complex scenarios is outstanding.

7 Implementation and Application of the CaaS Concept

Adhering to the Design Science Research Methodology, a CaaS prototype has been continuously implemented in WZL's M.A.R.S. laboratory to enable exposition to relying applications as part of the relevance cycle. This commences with the configuration of a suitable IT infrastructure in Section 7.1 followed by an introduction of the Large-Scale Metrology instruments involved and the implementation of the microservices identified in Chapter 5 using open source software (cf. sections 7.2 & 7.3). A responsive user interface reusing the machine-readable interfaces to the microservices and thereby allowing manual prototyping of service consuming applications is shown in Section 7.4. The chapter is completed with a selection of exemplary applications which have been realized using the CaaS demonstrator.

7.1 Established IT Infrastructure

The first step of implementing a CaaS system following the semantic structure of the *Internet of Production* presented in Section 2.2 and 4-layer architecture derived in Chapter 5 is the establishment of an appropriate IT infrastructure. Figure 7.1 summarizes the created ecosystem which is subsequently discussed in further detail. It does not follow a specific design or software stack paradigm found in literature, but rather is the outcome of the design cycles and embraces different technologies meanwhile identified as useful. Due to its integration into the M.A.R.S. laboratory, it exposes a certain brownfield characteristic. Effectively it only represents one, non-exclusive example for an infrastructure of a CaaS system.

The system is partitioned into three network layers: The instruments themselves[1] are accommodated in isolated private networks separated using vLAN tagging, enabling restrictive firewall policies. This allows for secure integration of devices using unsecured proprietary communication protocols or involving physical actors (e.g. robots or machine tools) demanding increased security measures. Each private network must contain at least one edge device running and exposing the instrument microservice layer to parties within the private network and acting as gateway into the subsequent enterprise/platform layer.

[1]This refers to the network interface the instruments possess for proprietary communication.

Technically, the private networks are not limited to Ethernet or Wi-Fi but can also be realized in Bluetooth, 5G or any other appropriate technology with suitable edge device. For the CaaS demonstrator infrastructure, Raspberry Pi minicomputers based on Linux and edge servers running on Microsoft Windows are present. Resilience and scalability within this layer are determined by the number and independence of individual instruments and edge devices.

The enterprise/platform network layer is named after its purpose to aggregate the instrument services from the individual private networks and provide the platforms to execute the microservices of a CaaS system's management layer (cf. Figure 5.1), while at the same time it should not be exposed to an audience broader than necessary. Moreover, the encapsulation in an own network layer allows the use of PaaS and SaaS or containerized infrastructure models. At WZL, a PaaS-solution is available in-house as virtualized respectively containerized server farm on a Microsoft Windows basis. As such, it enables the use of a wide range of software and programming languages, of which, among others, especially Python™ with Django, InfluxDB®, PostgreSQL, Node-Red, Node.js and JavaScript are used to implement the microservices as further discussed in Section 7.3. In addition, Keycloak™ as identity provider and RabbitMQ™ as MQTT-broker are hosted on this platform. With the execution on a server farm, high-availability features such as fail-over redundancy and load-balancing are built-in standard technologies adding resilience to the CaaS infrastructure.

Applications relying on CaaS reside within a third network tier, which is semi-public as any trusted consumer should be able to interact with the system. i.e. the tier must have a comparatively broad scope. In the present case, this scope extends to clients within RWTH Aachen University's network area[2]. Identification and name-resolving are realized using a Microsoft IIS Reverse Proxy exposing the microservices residing in the layers below to known clients that have been issued a valid SSL certificate. In this way, any device with networking capability can interact with CaaS, e.g. consumer devices such as tablets, online PLCs or robotic control nodes[3], for instance based on ROS. Scalability and resilience are responsibilities of the consumers except from the performance of the reverse proxy system.

The implemented infrastructure relies on HTTPs, MQTT and its websocket extension as core protocols in combination with JSON as serialization scheme, motivated by their ability to jointly provide the characteristics introduced in Section 6.1 and their ease-of-use from a practical point of view due to the extensive range of available open source software across different platforms. Therewith microservices are designable to expose REST interfaces. Intermediate implementations of the demonstration system included components interfaced OPC UA, although these implementations were discontinued bearing in mind the practical equivalence of different IoT protocols.

[2]In explicit, its *eduroam* and VPN network areas.

[3]Although the infrastructure allows the exposition to semi-public networks, it is still expected that robotic actors are protected within their own network scope.

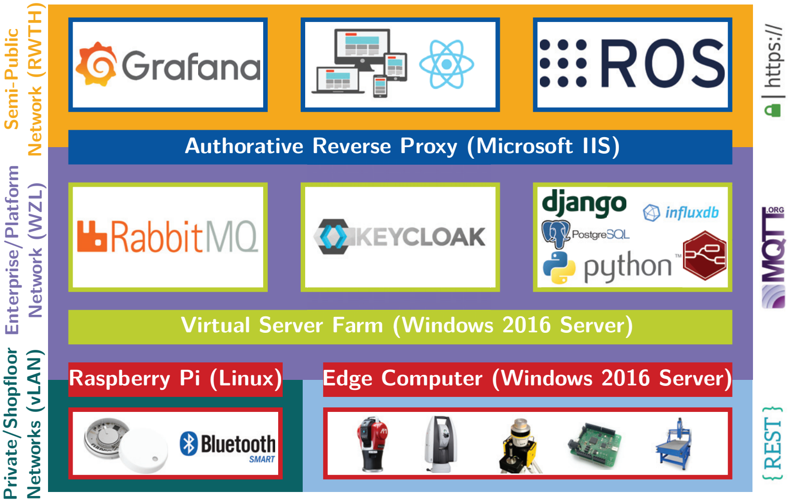

Figure 7.1: Three-layered network architecture elaborated and realized to implement a CaaS demonstrator system. The three tiers correspond to private, platform-wide and (semi-public) audiences of the respective applications and raw data.

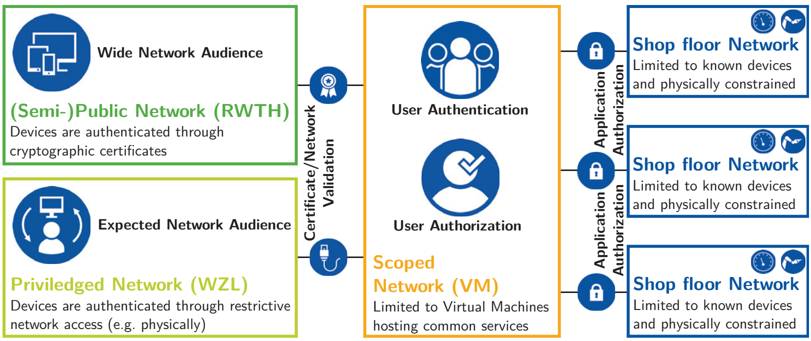

Figure 7.2: Implemented security measures between an application's end user and devices on the shop floor: Only devices authenticated by means of a client certificate or restricted networks can access the application's user interfaces hosted on virtual machines in a scoped networks. In addition, the user is authenticated and authorized against a centralized identity. Communication with devices on a shop floor is only possible through authorized applications residing on the virtual machines or from within the same shop floor network for direct control loops. In this figure, the depicted boxes correspond to firewalls.

An additional outcome of the multi-tiered network design is layered security mechanism depicted in Figure 7.2. The mutual client authentication ensures trust on a device level independent of the user. The latter is authenticated through its set of credentials by the OpenID Connect provider, such that authorization in applications can be decided in dependence of hardware and audience. The separation between the enterprise/platform and private network layers ensures that control over sensors and actors residing on the shop floor can only be exerted by corresponding applications. Within the private networks themselves, no extraordinary security measures are implemented, assuming the operator to physically avoid the integration of malicious participants. Moreover, this allows the efficient instantiation of local control-loops, processing the data either on a consuming actor, the edge device or even *in-network*[4] [GLEB19]. In total, all data paths envisaged in the architecture design earlier detailed in Figures 5.1 and 5.2 have been respected in the network design.

7.2 Used Large-Scale Metrology Instruments

This section describes the different Large-Scale Metrology instruments that have been used to create a prototype CaaS system in the M.A.R.S. laboratory. While the CaaS infrastructure is permanently available, the configuration and availability of the individual instruments is volatile. This does not impose limitations to CaaS as long as reconfigurations and availability are correctly fed back into the microservices' databases[5], but rather reviews the resilience of the implemented CaaS system. Therefore, the presented applications show different configurations and relevance cycles according to the research methodology due to their temporal incoherence.

The chosen models to implement the entity microservices should be regarded exemplary as they reflect a pragmatic approach regarding the mathematical models available for the different instruments in literature. Moreover, the dedicated development of these models is not within the scope of the CaaS development (cf. scope of research in Section 1.3), but rather is the abstracted interface for digital provisioning of the former. A brief introduction to each instrument is subsequently provided. As discussed in the previous section, the instrument microservice implementations focus on MQTT and HTTP/REST, assuming an equivalent realization is possible with other IoT protocols as derived in Chapter 4. Figure 7.3 exemplarily shows the serialization of the position information record summarized in Table 4.6.

[4] In-network processing refers to manipulating data packets using the available overhead in network operations, e.g. packet switching.

[5] This especially applies to the coordinate transformation parameters as defined in Chapter 3.

.../OBJ-LSMSystem/OBJ-Entities/OBJ-HOME_SMR/**VAR-Position**


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             43 de 1b ad ee cf 6b 6f 4d c8 66 fa 18 cc f3 1f 10 c3 95 0c
             f2 53 6c a1 57 25 04 d9 8c 9d 24 05 16 5c bf 34 0a 63 59 93
             e0 bd 0f fb 26 88 b3 ff 86 d0 11 f6 db 93 30 43 bc a3 44 63
             93 9f be 3b ee df d5 96 7c 58 5c 7c a5 56 e2 c3 28 dd 3a 79
             6b d5 f0 10 32 f1 12 7f"
}
```


Figure 7.3: JSON serialization of position information with according metadata, which can be for instance communicated via MQTT or HTTP and represents the nucleus of all developed applications. UUID, ontology, name and description have been omitted for legibility.

API Radian™ Laser Tracker

Two API Radian™ laser trackers are placed on the M.A.R.S. laboratory shop floor, of which one is fixed to a central pillar (cf. Figure 3.7) and the other is used semi-mobile on a tripod. Both are used with a range of standard 1.5 inch and miniaturized 0.5 inch SMRs as mobile entities. In addition, an Active Target is available. The manufacturer offers a C++ SDK employable to poll the laser tracker's measurement data at a rate of 1 kHz and control additional functions, e.g. to search for targets or lock the laser beam onto a known position. This SDK is used to implement the resource actions of the function model, which in turns are accessible as instrument microservice via a HTTP/REST and MQTT software layer. The latter have been implemented using Microsoft's cpprestsdk and Eclipse's Paho MQTT libraries. The use of the instrument's SDK imposes the use of Microsoft Windows based PC as edge device (cf. Figure 7.1) due to compatibility constraints. Moreover, it uses a proprietary, unsecured, UDP/TCP based communication protocol to the hardware controller of the laser tracker, which requires the use of the private network as introduced in the previous section (cf. Figure 7.2).

HUGHES et al. describe an elaborate model for the calibration of tracking interferometers, including 16 parameters covering different systematic effects due to misalignments, offsets, encoder limitations and scale errors [HUGH11]. Assuming the that compensations are applied to account for these systematic effects, the prevailing statistical uncertainty behavior is modeled following FORBES assuming uncorrelated measurements in spherical coordinates (r, φ, θ) following normal distributions with variances depending on the target distance [FORB12, p. 5]. Using an aproriate jacobian matrix $\mathbf{J}_{spherical}$ to account for the transformation to cartesian coordinates, one obtains the covariance prediction stated in eq. 7.1.

$$\hat{\mathbf{V}}\left(\hat{\boldsymbol{p}}\right) = \mathbf{J}_{spherical} \cdot \begin{pmatrix} \sigma_{r,0}^2 + \sigma_{r,1}^2 \cdot ||\hat{\boldsymbol{p}}||^2 & 0 & 0 \\ 0 & \frac{1}{\cos^2\theta}\left(\sigma_{\varphi,0}^2 + \frac{\sigma_{\varphi,1}^2}{||\hat{\boldsymbol{p}}||^2}\right) & 0 \\ 0 & 0 & \sigma_{\theta,0}^2 + \frac{\sigma_{\theta,1}^2}{||\hat{\boldsymbol{p}}||^2} \end{pmatrix} \cdot \mathbf{J}_{spherical}^T \tag{7.1}$$

The coverage model $\mathcal{B}$ is a simple line of sight function respecting the range of the distance measurement and angular encoders as denoted in eq. (7.2), while the angular range in eq. (7.3) is evaluated as function of the SMR's natural acceptance angle compared to the direction of the beam.

$$\mathcal{B}\left(\hat{\boldsymbol{p}}\right) = \begin{cases} \text{true} & \varphi\left(\hat{\boldsymbol{p}}\right) \in \Phi_{valid} \quad \wedge \quad \theta\left(\hat{\boldsymbol{p}}\right) \in \Theta_{valid} \quad \wedge \quad r\left(\hat{\boldsymbol{p}}\right) \in R_{valid} \\ \text{false} & \text{else} \end{cases} \tag{7.2}$$

$$\mathcal{Q}\left(\hat{\boldsymbol{p}}, \hat{\boldsymbol{n}}\right) = \arccos\left(-\frac{\hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{n}}}{||\hat{\boldsymbol{p}}|| \cdot ||\hat{\boldsymbol{n}}||}\right) \overset{?}{\leq} \sphericalangle_{acceptance} \tag{7.3}$$

Leica AT960™ Laser Tracker

A third laser tracker is included in the demonstrating setup with the Leica AT960™. Due to the physical similarity to the API Radian™, the same uncertainty and coverage models with adapted instance-specific parameters are used. In addition to 1.5 inch SMRs, the Leica T-Mac is available as target which allows for orientation measurement using a photogrammetric enhancement of the classical laser tracker setup. Likewise, an edge computer with Microsoft Windows runs a service container wrapping the proprietary communication using the available C# SDK and MQTTnet library. At the time of writing, the exploitability of in-network processing is investigated using the real-time feature pack available for this instrument.

Nikon iGPS™

Approximately half of the shop floor is covered by a Nikon iGPS™ system with six transmitters. From a functional point of view, the mobile units are modeled on frame level which is closer to the relying applications, while a model on PCE level would have been equally possible. It comprises the following entities:

- 1 i6 Scale bar and long range probe (6 PCEs)
- 1 iProbe with attached 0.5 inch probe (4 PCEs)
- 2 custom-built frames (4 PCEs)
- 6 i5 integrated sensors (2 PCEs)

By design, the iGPS™ system requires a private network with WiFi access point and computer with Microsoft Windows for operation. The proprietary user interface can be operated in parallel with a C# interface, which is used to create the required service layer in MQTT and HTTP/REST using the MQTTnet and ASP.net libraries.

As summarized by QUINDERS, multiple performance studies have been carried out by different research groups to estimate the uncertainty of iGPS measurements in different configurations, but no de-facto standard model has emerged [QUIN18, pp. 46-55]. Two possible approaches are discretized uncertainty maps based on reference measurements or numerical simulations, as for instance reported by SCHMITT et al. [SCHM10], which are both encapsulable as microservices with the interface suggested in Section 6.1. In the reference scenario, the system is modeled as set of $i = 1 \ldots n_{transmitters}$ transmitters each measuring the intersection angles φ and θ_i and possessing known positions $\tilde{\boldsymbol{T}}_i$ and orientations $\tilde{\mathbf{R}}_i$. For each transmitter with line of sight to a PCE at position $\hat{\boldsymbol{p}}$, eq. (7.4) holds, such that an (overdetermined) linear set of equations can be solved for the unknown distances r_i with measurements for φ_i and θ_i. To implement $\hat{\mathbf{V}}\left(\hat{\boldsymbol{p}}\right)$, the latter are assumed as main uncertainty contributors following normal distributions with variances as defined in eqs. (7.5) & (7.6) [HUGH10, p. 4]. The propagation to Cartesian coordinates through the aforementioned set of equations is then performed by means of a Monte Carlo simulation.

$$\tilde{\boldsymbol{T}}_i + \tilde{\mathbf{R}}_i \cdot \begin{pmatrix} -\sin\varphi_i \cos\theta_i \\ \cos\varphi_i \cos\theta_i \\ \sin\theta_i \end{pmatrix} \cdot r_i = \hat{\boldsymbol{p}} \tag{7.4}$$

$$\sigma^2_{\varphi,i} = \sigma^2_{\varphi,0} + \frac{\sigma^2_{\varphi,1}}{r_i^2} \tag{7.5}$$

$$\sigma^2_{\theta,i} = \sigma^2_{\theta,0} + \frac{\sigma^2_{\theta,1}}{r_i^2} \tag{7.6}$$

The visibility for each transmitter is determined based on a maximum elevation and $\mathcal{B}$ is considered true if the visibility to at least three transmitters is granted[6]. The angular acceptance $\mathcal{Q}$ is determined as in eq. (7.7) based on the orientation of the PCE with respect to the z-axes of the individual transmitters.

$$\mathcal{Q}\left(\hat{\boldsymbol{p}}, \hat{\boldsymbol{n}}\right) = \arccos\left(\tilde{\mathbf{R}}_i \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \cdot \hat{\boldsymbol{n}}\right) \overset{?}{\leq} \sphericalangle_{acceptance} \quad \text{for at least 3 transmitters} \tag{7.7}$$

Pozyx™ UWB System

Another half of the shop floor is equipped with a network of six Pozyx™ UWB anchors, allowing three mobile tags to be located within the UWB signal range. Their orientation is determined on-board using an Inertial Motion Unit (IMU) and does therefore not rely on the anchors. Due to the large number of obstacles and other line of sight constraints, a stable operation could only be achieved with an update rate of 1 Hz. While elaborate models for UWB positioning algorithms exist [RIDO18], for the same reasons, continuous operation with an observed uncertainty below 50 cm could not be achieved, although setups reported in literature achieve uncertainties below 10 cm[7]. As moreover no adequately modelable behavior was observed, a conservative, constant function was used as uncertainty contribution model $\hat{\mathbf{V}}$. Due to the large uncertainty contribution and typical relying applications, traceability is no concern for this instrument. The coverage model $\mathcal{B}$ and the angular acceptance function $\mathcal{Q}$ are implemented as always positive considering the arbitrary orientation allowed by the physical principle and no a priori visibility constraints.

[6] Mathematically, two transmitters are sufficient but in practice, stable operation is typically observed with visibility to at least three.

[7] It is assumed that the observed behavior was rather caused by the explicit laboratory shop floor configuration than shortcomings of the instrument.

The UWB system communicates to an edge computer through a master anchor using a serial interface. On the edge device, the manufacturer's open source Python SDK is used to provide the instrument microservice in MQTT and HTTP/REST using the paho-mqtt and aiohttp packages.

BZT PFU-S2-2015-G

As discussed in Chapters 4 and 6, the chosen modeling perspective allows to include non-mobile kinematics into the CaaS service. This approach is followed in the demonstrator setup by including a BZT PFU-S2 2015-G machine tool with its functional point as mobile entity into the scenario. As shown by PETEREK, a calibrated machine tool can be employed for traceable on-machine measurements of geometric features, where the volumetric performance enters the overall uncertainty budget [PETE17]. This corresponds to the uncertainty contribution model $\hat{\mathbf{V}}$, which can be established empirically by the statistical behavior respectively uncertainty observed during calibration measurements of the machine tool. Coverage $\mathcal{B}$ and angular acceptance $\mathcal{Q}$ are trivial functions reflecting the working volume and the inability of rotating the tool for an FYXZ kinematic chain. In addition to conventional calibration using an API XD-Laser™ Precision, the BZT PFU-S2 2015-G can be calibrated in CaaS consuming application using one of the available laser trackers as further described in Section 7.4. Moreover, the machine tool also serves as experimental setup for newly developed sensor systems permanently integrated into its axes as shown in Figure 7.4, allowing for calibration in parallel to machining processes and on-machine measurements and advancing the idea of machine tools becoming traceable instruments within a CaaS system [MONT18].

The numerical controller of the machine tool runs on Microsoft Windows system and allows to include a custom middleware implemented as Dynamic Link Library (DLL) called within the 5 ms control cycle, which is employed to establish an MQTT stream of the functional point's current position. Current efforts within the machine tool industry under the *umati* initiative strive towards a unified interface based on OPC UA, which may allow a generic and seamless integration of further machine tools in the future [VDWE19].

Figure 7.4: Multi-sensor setup consisting of two corresponding units (mobile and fixed) that is integrated into an axis of the BZT PFU-S2 2015-G machine tool included in the demonstrator scenario and forming part of the research activities to online machine tool calibration in turns facilitating traceable on-machine-measurements. The shown setup is capable of measuring 5 degrees of freedom by using fibre-based interferometer and visible laser in combination with two CMOS cameras [MONT18].

7.3 Realization of Management Microservices

While the implementation of instrument microservices is covered on per instrument at edge level, the management microservices of the CaaS demonstration system are designed to reside in the enterprise/platform layer. This decision allows to leverage hardware scalability for complex modeling or ranking algorithms and enables the interaction of other applications with CaaS for planning purposes without traversing security-sensitive networking layers. Consequently, the implementations account for executability on the virtual server infrastructure presented in Figure 7.1.

Instrument Modeling $\mathbb{M}$

For the demonstration scenario, the instrument models associated in the previous section are independently implemented in Python using numpy for optimized calculations. An HTTP interface is implemented using asyncio to expose $\hat{\mathbf{V}}\left(\hat{\boldsymbol{p}}, \hat{\boldsymbol{q}}\right)$, $\mathcal{B}\left(\hat{\boldsymbol{p}}\right)$ and $\mathcal{Q}\left(\hat{\boldsymbol{p}}, \hat{\boldsymbol{n}}\right)$ with requests and responses serialized in JSON. Each instrument modeling microservice is reachable under its own URL, reproducing a scenario where it may be provided and hosted by an external party, e.g. NMI.

Microservices $\mathbb{E}, \mathbb{A}, \mathbb{P}$

All microservices related to entity management and allocation are implemented in Python using the django package. The latter allows for model-driven SQL-database design and usage, which is pursued following the entity properties defined in Table 6.2. The three microservices act on the common database each offering a REST API over HTTP in JSON format[8]. Figure 7.5 shows an excerpt of an example query result for known entities in $\mathbb{E}$. All entities are additionally attributed a system-wide unique identifier to facilitate administration. Characteristics $\mathcal{B}$, $\mathcal{Q}$, $\hat{\mathbf{V}}$ are represented as URL references to the according microservices $\mathcal{M}$ to account for arbitrary and opaque functional implementations, for which an example query is shown in Appendix B. In addition, $\mathbb{E}$ maintains a list of instruments grouping accordingly shared entity characteristics, explicitly also providing the according transformation from local to global coordinates including parameter covariance in the representation defined in eqs. (3.6) and (3.7). A human readable name and color code are introduced for usability purposes, as can be seen in the serialization example in Figure 7.7

The entity allocation microservice $\mathbb{A}$ administrates assignments of entities to users[9] and service levels over defined time spans by means of their unique identifiers. Three different service levels are available:

[8]For the implementation, the django-rest-framework package is used.

[9]An application is expected to be always executed on behalf of a user to enforce according authorization policies.

- **READ** The consumer wants to read the entity's current position information but neither intends to take physical nor software control of it. This level is typical for monitoring and reporting applications. Read allocations can coexist with other read and use allocation.

- **USE** The user explicitly wants to use the entity for an application and probably physically govern its movement or built-in functions. Consequently, only one use allocation can exist at the time.

- **MAINTENANCE** The entity will be unavailable for the allocated time span, e.g. due calibration, cleaning or battery change. No other allocation of any kind can coexist.

The allocation microservice can be enhanced to enforce access policies for users based on arbitrary criteria (e.g. time budgets or training certificates), which is incorporated in the demonstrator implementation evaluating user roles defined in $\mathbb{U}$. Figure 7.6 contains a serialized representation of a corresponding entity allocation in $\mathbb{A}$, which, among others, is leveraged to create calendar views as in Figure 7.10.

The planning microservice $\mathbb{P}$ is designed to return a sorted and filtered view of $\mathbb{E}$ based on query parameters logically limiting the applicable entity properties. Therefore it explicitly implements the Γ-ranking algorithm proposed in eq. (6.4) and internally calls the functions $\mathcal{B}$, $\mathcal{Q}$, $\hat{\mathbf{V}}$ of the according entity models for calculation of the metrics.

User Service $\mathbb{U}$

The user service is implemented using Keycloak™ as existing, open source solution for user and account management. It follows a single sign-on approach with an OAuth2 and OpenID Connect compliant HTTP API. It acts as identity provider for all services requiring authentication and authorization, using role-based access control to issue and check permissions, e.g. whether a certain user is allowed to operate a distinct instrument.

Database Service $\mathbb{X}$

Although not explicitly required by CaaS, the demonstrator system has been extended with a database service based on InfluxDB®, allowing to store measurement data in a time-series manner. As such, it can be regarded as external microservice $\mathbb{X}$ in the perspective of Section 5.2. It is also used to log the environmental conditions (temperature, humidity and pressure) of a distributed sensor system consisting of RuuviTags™ placed at different locations on the shop floor. Referring to the *Internet of Production* paradigm presented in Section 2.2, this microservice constitutes a part of the smart data layer.

GET metrology.wzl.rwth-aachen.de/mars-backend/**entities/entities/8800405b-eb41-4ab7-8404-c34071a9b4d2**


```json
{
    "key": "8800405b-eb41-4ab7-8404-c34071a9b4d2",
    "environment": {
        "uuid": "d879aac1-76a8-493d-b73d-84573f487293",
        "name": "Default",
        "T": [18.0, 25.0],
        "p": [93000.0,110000.0],
        "H": [0.05,0.95]
    },
    "instrument": "radian-e7ccdff2-764d-42b2-91af-4dd52f9187e6",
    "uuid": "OBJ-HOMESMR",
    "name": "Default SMR",
    "active": false,
    "B": "http://localhost:9200/laser_tracker/B",
    "Q": "http://localhost:9200/laser_tracker/Q",
    "V": "http://localhost:9200/laser_tracker/V",
    "t_measure": 0.001,
    "t_dead": 0.01,
    "f_sample": 1000.0,
    "v_max": 10.0,
    "O": false,
    "F": "REFLECTOR",
    "R": true,
    "T": true,
    "K": true,
    "Z": false,
    "cost": 0.0,
    "siblings": []
}
```


Figure 7.5: Representation of entity characteristics as return by $\mathbb{E}$ serialized in JSON. The properties $\hat{\mathbb{V}}$, $\mathcal{B}$ and $\mathcal{Q}$ are represented as URLs to an implemented instrument modeling microservice $\mathbb{M}$. An additional UUID has been introduced to facilitate primary key management in the database.

GET metrology.wzl.rwth-aachen.de/mars-backend/**allocations/e9834b68-e7db-4c73-8ab1-4690a9604820**


```json
{
    "key": "e9834b68-e7db-4c73-8ab1-4690a9604820",
    "level": "USE",
    "starts_at": "2019-09-10T10:00:00Z",
    "ends_at": "2019-09-10T11:00:00Z",
    "entity": "8800405b-eb41-4ab7-8404-c34071a9b4d2",
    "user": "mnt"
}
```


Figure 7.6: Representation of an allocation for the entity denoted above returned by $\mathbb{A}$ with a time frame serialized according to RFC3339 [RFC3339] and user key corresponding to the central identity service.

GET metrology.wzl.rwth-aachen.de/mars-backend/**entities/instruments/ radian-e7ccdff2-764d-42b2-91af-4dd52f9187e6**


```
{
    "thing_id": "radian-e7ccdff2-764d-42b2-91af-4dd52f9187e6",
    "entities":  [...],
    "bases" : [...],
    "transformation": {
        "uuid": "abb4a927-15de-4206-bff5-4f09673d1cda",
        "a": 0.5961765368581369,
        "b": -0.00012769971594517315,
        "c": -0.005436523116230552,
        "d": -0.8029026226724223,
        "tx": -1.7871860093252696,
        "ty": 4.550559767193732,
        "tz": 1.5514544330753086,
        "covariance": {
            "a,a": 1.3745990251982182e-09,
            "a,b": 3.759881222365889e-11,
            "a,c": -1.1287634618997848e-11,
            "a,d": -2.655843260602885e-10,
            "a,tx": -5.331847670850108e-09,
            "a,ty": 5.065852372990805e-10,
            "a,tz": -2.9542723932665584e-10,
            "b,b": 6.419910361387785e-11,
            "b,c": 2.184769353630746e-11,
            "b,d": -3.5568456063590854e-11,
            "b,tx": -2.7482013366576845e-10,
            "b,ty": 1.900681413033548e-10,
            "b,tz": 2.3475934575918625e-11,
            "c,c": 6.887268094747749e-11,
            "c,d": 1.6774375519345153e-12,
            "c,tx": -6.104752064506547e-11,
            "c,ty": 6.970455479475664e-12,
            "c,tz": 1.5213183958097581e-10,
            "d,d": 7.579966336573327e-11,
            "d,tx": 1.1088356078274229e-09,
            "d,ty": -2.316485027314211e-10,
            "d,tz": 7.45505512033685e-11,
            "tx,tx": 2.1224576276944857e-08,
            "tx,ty": -2.408984673449033e-09,
            "tx,tz": 9.767525131505078e-10,
            "ty,ty": 1.0122972082821898e-09,
            "ty,tz": -1.8779000328852317e-10,
            "tz,tz": 5.626245835871672e-10
        },
        "time": "2019-09-09T12:09:31.247343Z"
    },
    "name": "API Radian 60554",
    "color": "#CC071E",
    "active": true
}
```


Figure 7.7: Representation of instrument information managed within 𝔼 serialized in JSON, containing the coordinate registration parameters as defined in Chapter 3.

7.4 Novel and Existing Applications as CaaS Consumers

Throughout the design cycles, multiple applications using the established CaaS system to different extents have been instantiated as consumers and will be described within this section. All consumers either use a request/response scheme to access the data of triggered measurements or publish/subscribe scheme for continuous measurements. Figure 7.8 summarizes the interaction of a consumer in the demonstration system with the microservices and instruments.

A human interface to the CaaS system has been developed as as responsive web application based on the React framework initiated by Facebook Inc., focusing on desktop and conventional tablets as interacting devices. It relies on the same interfaces as any other application, i.e. it constitutes a CaaS consumer itself. On its main page depicted in Figure 7.9, it effectively shows a map with markers representing position of all active entities in the coordinate system of the M.A.R.S. laboratory's CAD model, which is included in a 2D top view. By selecting a marker, more details of the position information extracted from the record (cf. 7.3) are retrieved. The location of the instruments' bases and polygonal schematics of their coverage are provided for convenience[10].

Access to the applications is controlled by corresponding user roles within the OpenID Connect user services. A CaaS administration role grants access to an additional backend editing user interface to modify the data basis for $\mathbb{E}$, $\mathbb{A}$ and $\mathbb{P}$, i.e. adding or modifying instruments and entities in the CaaS system. Therewith, the developed application comprises a role-aware single point of contact for human operators simultaneously acting as supervising tool. Suitability and usability have been continuously proven and improved throughout the relevance cycles based on feedback by different users. A second view shown in Figure 7.10 presents a list of available entities to the user, including a modal view containing the entity properties as defined in Table 6.2 and a calendar view showing existing allocations for the entity in question. Interaction is both possible by placing an allocation request or providing a set of reference locations to evaluate the instrument models through the ranking algorithm implemented in $\mathbb{P}$ and obtain a sorted list of entities. This allows for prototyping the behavior of other CaaS consumers at an early stage without the need for explicit programming.

Multiple applications benefit from the developed unified and simplified interface for Large-Scale Metrology instruments, especially laser trackers. In a CaaS view, the examples presented hereafter correspond to a consumer which manually chooses an entity based on expert knowledge.

[10] The polygonal approximation as guidance for a human operator is not equal to the coverage function provided by the instrument modeling services but rather a user-oriented approximation.

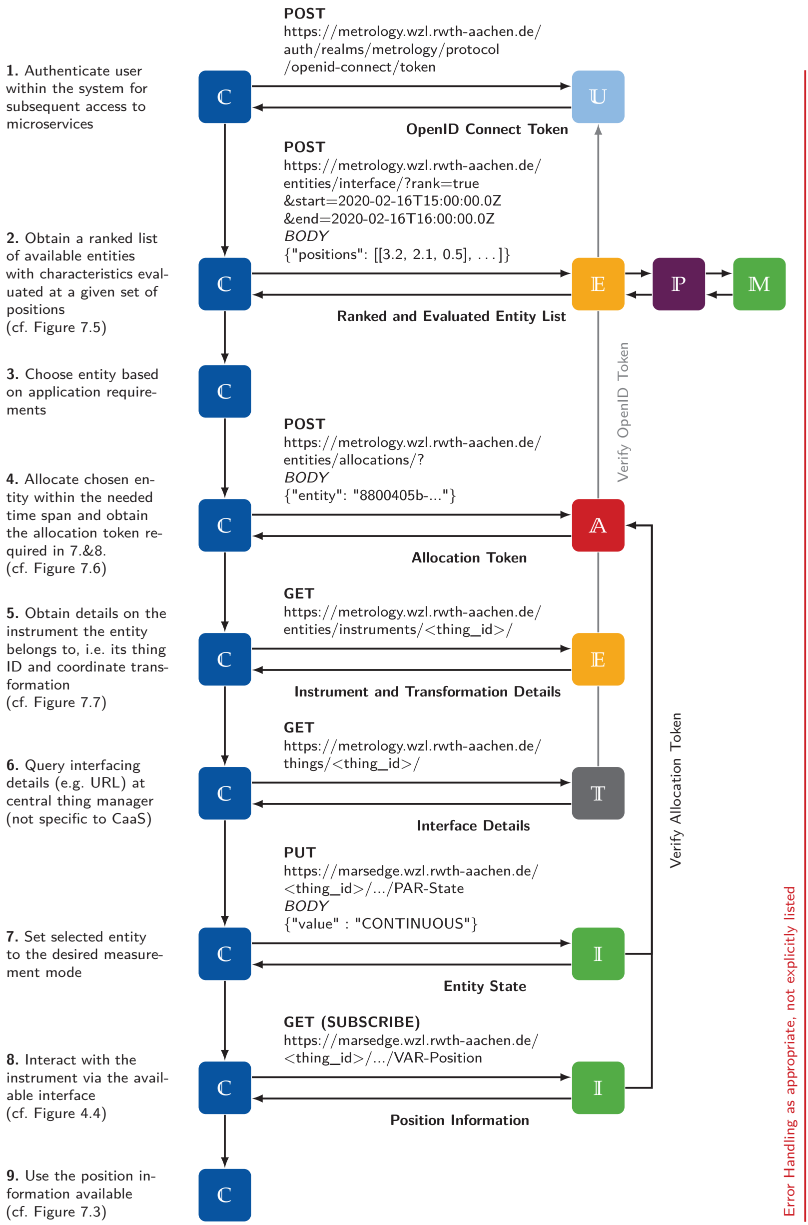

Figure 7.8: Overview of the total interaction of a consumer with the CaaS demonstrator system to utilize an entity for an application. The denoted URLs correspond to the reference setup, while request bodies have been shortened for legibility. The thing manager $\mathbb{T}$ is specific to the used infrastructure as general asset manager.

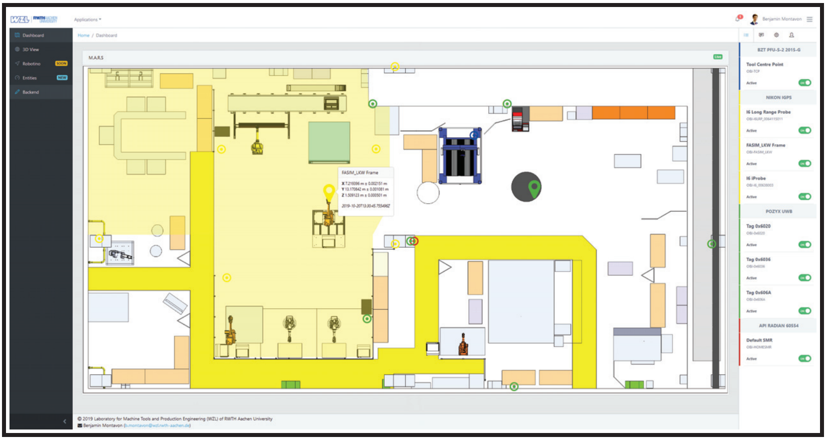

Figure 7.9: Main user interface to the CaaS prototype system designed as responsive web application at the same time providing an overview of the current situation on the shop floor.

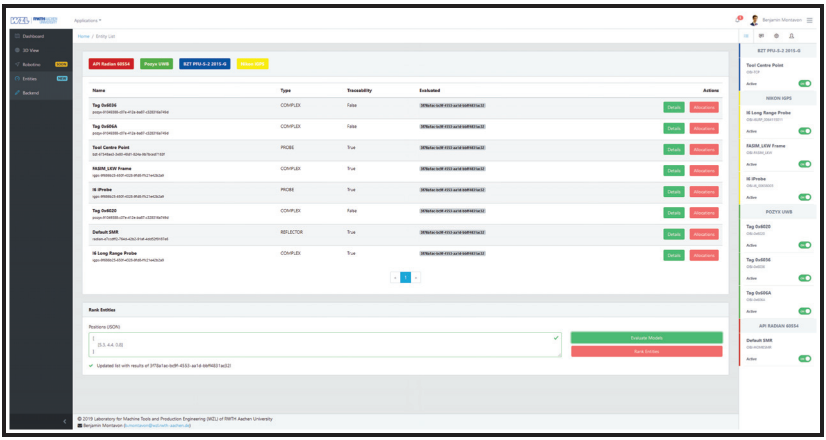

Figure 7.10: Main view of the entity management functions included into the CaaS main user interface allowing to prototype consuming applications before implementing the according queries to the machine-readable interfaces of $\mathbb{E}$, $\mathbb{A}$ and $\mathbb{P}$. Further screenshots are included in Appendix G.

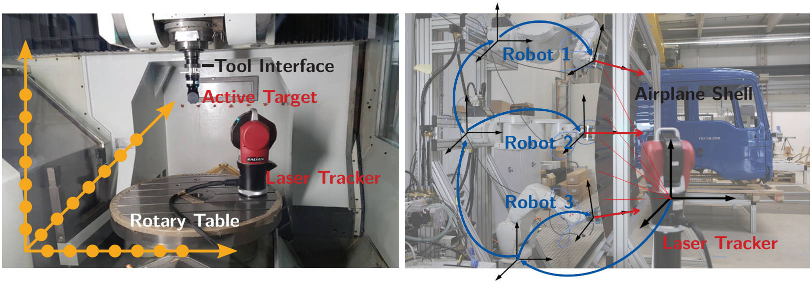

Figure 7.11: Applications consuming position information obtained with a laser tracker interfacing with the instrument microservice 𝕀. **Left:** Calibration of a five-axis machine tool using an Active Target as described by MONTAVON et al. [MONT19]. **Right:** Measurement of the structural deformation of an airplane shell using six sequentially captured SMRs as described by BERTELSMEIER [BERT19].

Figure 7.11 shows an experimental setup measuring the deformation of an airplane structure in reaction to forces exerted by three robots replicating an assembly situation. Therefore the inner side of the shell has been fitted with six SMRs which are measured sequentially. The interaction flow depicted in Figure 4.4 is used such that the reflectors represent individual entities to which the laser tracker locks upon activation. Measurement data is discretely retrieved on a request/response basis, i.e. READ operations on the VAR-Position variables called from the main control loop implemented in Matlab™.

Another application is the calibration of machine tools as shown in Figure 7.11, where a Large-Scale Metrology instrument serves as a reference over a grid of locations where both the current position of the functional point indicated by the machine tool and the position of a mobile entity attached close to it are captured. Using a matrix representation of the rigid body model, geometric error motions according to ISO 230-1:2012 [ISO230-1] can be estimated by solving a overdetermined system of linear equations using a least squares approach. The covariances of the respective measurements enter in the equation system's weighting scheme. The principal instrument used during the development of this calibration technique was an API Radian™ laser tracker in combination with either a conventional SMR or Active Target, however, any entity with sufficient coverage and angular range within the machine tool's working volume and acceptable uncertainty contribution could be employed. This reflects in the adhering software implemented in Python™ and Node-Red (cf. Figure 7.12), which relies on the CONTINUOUS measurement mode and subscribes to VAR-Position after activation of the respective entity. The continuous sampling is used to detect the stationary locations within the calibration strategy without need for bilateral communication with the machine tool's controller and enables detection of remaining vibrations at the mobile entity [MONT19].

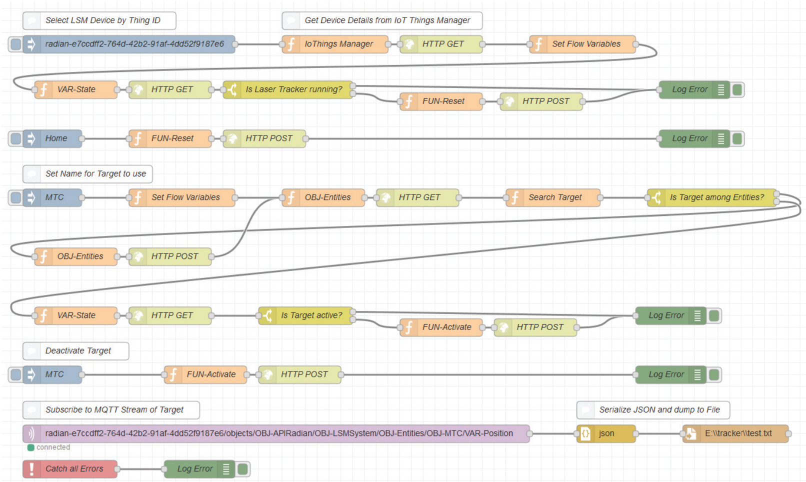

Figure 7.12: Excerpt of a Node-Red based control loop for using a Large-Scale Metrology instrument for machine tool calibration, e.g. a laser tracker as shown in Figure 7.11.

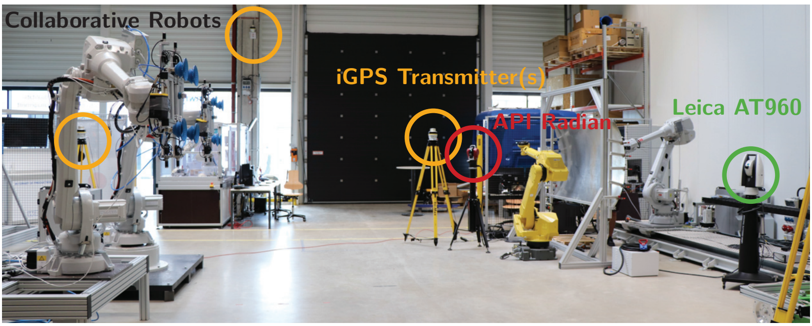

Figure 7.13: Setup for validation experiments of the assembly of a windshield to a truck cabin as part of a research project. The motion of both robots' end effectors was controlled using position information provided by the indoor GPS system, while the resulting trajectories were captured using two laser trackers.

The implemented CaaS prototype was furthermore utilized in a research project investigating a model-based control loop for collaborating robots inserting a windscreen into a truck cabin in motion, which is a continuation of the work by NICKSCH et al. and STORM et al. [NICK18, STOR17] within the same research group. The principal metrological feedback is inferred from a custom indoor GPS frame attached to each robot's end effector. Figure 7.13 shows a setup with two additional laser trackers for an experimental validation of the implemented control loops such that at the center of each end effector an SMR is mounted to enable measuring the actual trajectory followed by the robots. For all involved Large-Scale Metrology instruments, the CONTINUOUS mode with subscriptive data retrieval is used for simultaneous acquisition.

A more generic integration of CaaS into robotic applications is instantiated by a consumer bridging the data transmitted in a publish/subscribe pattern by MQTT into the messaging system used in the *Robot Operating System (ROS)* ecosystem. The latter provides a framework for platform-independent realization of complex robotic applications, especially including mobile manipulators and is one of the major software tools used for research and development of novel robotic applications [GARB13]. The brigde is implemented to republish the coordinate transformations available in $\mathbb{E}$ in ROS' `geometry_msgs/Transform` format and current position information in the `geometry_msgs/PoseWithCovarianceStamped` format[11]. As the latter two do not support any unit information, all length quantities are converted to millimeters before being republished, while rotations are consistently expressed in quaternions. The message topics are uniquely defined by translating the hierarchical interface identifier. Herewith the inclusion of data originating from the CaaS system into ROS nodes is consistently enabled with minimal effort.

In addition to direct CaaS consumers, within the infrastructure presented in Section 7.1 an instance of Grafana® was installed, allowing to create temporal dashboard views of the data stored in database services and thereby viewing arbitrary data stored in time series format and related to the M.A.R.S. laboratory. Appendix G additionally shows a view summarizing the environmental conditions recorded by the distributed RuuviTag™ system. This web application extends the system's user interaction introduced at the beginning of this section by providing historic views accessible with the same user identity respectively device.

[11] Definitions of both formats are included in Appendix H.

7.5 Intermediate Summary

A CaaS prototype system serving as design artifact for the relevance cycles has been successfully and continuously implemented in the M.A.R.S. laboratory. Among various development stages, it comprised three laser trackers (API Radian™/Leica AT960™), a Nikon iGPS™ system, a Pozyx™ UWB setup, and a machine tool as Large-Scale Metrology instruments. For all instruments, a model-based interface adhering to Chapter 4 has been implemented. In general, the architectural dissection into microservices and protocol-abstraction previously developed have facilitated the embodiment of the system. Its applicability is sustained by multiple consuming applications being implemented on its basis, involving a deformation test stand for aerospace structures, machine tool calibration and experimental setup for a dynamic, metrology-based, collaborative assembly operation. Moreover, a user interface application providing human-friendly access to the CaaS prototype's service endpoints has been deployed. The elaborated IT infrastructure has been proven applicable to accommodate the microservices identified in Chapter 5 and appropriate in terms of availability, performance and security. Therewith a secondary outcome of the CaaS prototype design is a reference example for a system's architecture and responsive user interface providing world-wide, secure access to data and applications related to the M.A.R.S. laboratory.

The successful technical materialization of CaaS supports the principal research objective as reviewed in Chapter 8 and reconfirms the research guiding subquestions on implementation level.

8 Critical Reflection and Outlook

Throughout this thesis, the Coordinate as a Services (CaaS) paradigm has been introduced and investigated utilizing the method of Design Science Research. The principal research objective can be regarded as successfully achieved based on the affirmation of the research guiding questions (cf. Table 8.1) in conjunction with the implementation and exposition of a prototype system as functional artifact. Primary motivation of the described research is to provide a virtual reference coordinate frame to an audience of arbitrary applications, including automated systems, residing on a shop floor using multiple, distributed Large-Scale Metrology instruments. While availability, performance and heterogeneity of these instruments are increasing, the state of the art in software dedicated to the concurrent use of multiple LSM instruments is represented by so-called commercial applications for portable 3D metrology, e.g. SpatialAnalyzer™. Advances in platforms and architectures for heterogeneous sensor systems and service-oriented approaches have not yet been leveraged in the domain of Large-Scale Metrology. In contrast, novel paradigms in assembly automation as well as the demand for shorter quality control loops motivate the potential benefits of a servitized, virtual reference coordinate frame.

1. *Can position information of heterogeneous Large-Scale Metrology instruments be transformed into a global coordinate system?*	✓
2. *Can a model-based, protocol-agnostic interface to Large-Scale Metrology instruments be defined based on technology-independent characteristics?*	✓
3. *Does an appropriate system architecture respecting interfaces and decomposition to implement and servitize a virtual, metrology-based reference frame exist?*	✓
4. *Can the individual, technologically heterogeneous instruments be managed as service resources without interacting with superordinate planning from an industrial application's perspective?*	✓
Can position information within a virtual reference frame defined by multiple, heterogeneous Large-Scale Metrology instruments be provided to industrial applications as a service with abstracted interface?	✓

Table 8.1: Summary of the responses to the principal research objective and research guiding questions formulated in Chapter 1. Rationales are included in the intermediate summaries of Chapters 3 - 6.

The heterogeneity of instruments is respected on a physical level through a mathematical model and development of a novel method to register the local coordinate systems and transform the provided position information to a global coordinate system. It was investigated and validated in Monte Carlo simulations and in experiments using two laser trackers and an indoor GPS system. While the resulting uncertainty contribution is slightly higher compared to the situation where the same mobile entities (e.g. SMRs) can be used, the developed method is artifact-free, allows for analytic propagation of uncertainties and has a high potential for automation.

On interaction level, a functional model from the perspective of mobile entities is established as basis for model-based interface design, introducing an abstraction layer to address the instruments' heterogeneity. Moreover, the model respects distinct resource classes, allowing a systematic mapping to different IoT protocols. Therewith standardized protocols such as OPC UA and MQTT can be applied to implement a CaaS system without limiting the concept to a single technology and thereby mitigating deprecation risks, although this approach comes at the cost of omitting capabilities of individual protocols. The integration of LSM instruments effectively acquiring a point cloud instead of individual mobile entities is conceptually considered, but may not be optimal. In addition to the aspect of interaction, a route to integrate traceability on a metrological and digital level using a distributed ledger approach is introduced. However, the latter still requires a more comprehensive validation for different industrial use cases with multiple stakeholders and a close alignment with future activities in the field of Digital Calibration Certificates.

The overall service-orientation is incorporated by identifying therefore necessary subtasks and dissecting them into microservices. The microservice approach is chosen to meet the requirements of modern manufacturing IT bearing in mind the alternative concepts of multiagent-based systems and holonic manufacturing systems, which are retrospectively considered as equally viable alternatives. Embraced benefits of the microservice design paradigm are scalability, resilience, greater autonomy of the components and faster development cycles for the implementation of new or modification of existing CaaS systems. Thereby a high degree of flexibility in hardware choice (i.e. cloud, near-edge and edge computing) and architecture design is introduced. This includes the possibility to delegate the implementation of individual microservices opaquely to third parties preserving intellectual property, e.g. providing virtual models of the used instruments by their manufacturer or an NMI. For the distribution of microservices in an explicit architecture, a four-layer proposition comprising instruments, instrument abstraction, management services and user/consumer interaction as well as considering resilience and scalability on hardware level is elaborated. This proposition must be regarded as non-exclusive as the validation does not unveil the inadequacy of other architecture approaches. Accordingly, the four-layer structure for instance conceptually agrees with the four principal levels of the *Internet of Production* framework, while other reference architectures for industrial IoT applications reported in literature distribute the same functionality among three (e.g. things, insights, action [Wass19]) to five layers (e.g. objects, object abstraction, service management, application layer, business layer [AlFu15, p. 2349]).

With the Large-Scale Metrology instruments becoming service resources, the need for resource management emerges, which is approached by identifying a set of common metrological capabilities and introducing an interface to evaluate virtual models of the instruments for more concise estimates of coverage, angular acceptance and expected covariance. The formulation of required metrological capabilities is expected to be deduced by the task the service consumer is implementing. To integrate with a superordinate planning system, task assignment and recommendation of instruments and their mobile entities as resources are decoupled. A mathematical greenfield approach to resource recommendation based on phase space maximization is introduced and evaluated on a simulation basis. While its general applicability could be confirmed to a limited extent, the configuration of instruments within the service volume, unique capabilities, assignment order and further boundary conditions can become overruling effects. Therefore the total interaction flow includes an allocation microservice treating assignments as temporal problem based on an arbitrary rationale. As a result, instrument respectively mobile entity choice are possible following the recommendation internal to CaaS based on ranking following the aforementioned metric, using an external system, or even manually incorporating human expert knowledge. This decoupling is further sustained by the partial impracticality to follow global optimization objectives in a confined subsystem.

The scientific advances accumulate in the successful introduction of the *Coordinates as a Service (CaaS)* paradigm and the implementation of a reference system at the M.A.R.S. laboratory in conjunction with an adhering IT infrastructure. Its utility is validated through individual applications acting as service consumers of the reference system. As further discussed in Section 8.1, research methodology and impact are evaluated largely positive. Section 8.2 discusses potential industrial scenarios for which CaaS can be an enabling technology. Apart from the further research potential stated in Section 8.3, a major question is how CaaS can serve as blueprints for other domains to leverage the benefits identified.

8.1 Critical Reflection of Research Methodology and Impact

The chosen methodology of Design Science Research is retrospectively considered as appropriate to approach the declared research objectives [HeVn10]. The elaboration of the reference system presented in Chapter 7 serving as artifact commenced immediately with the beginning of the course of research. With the iterating procedure, a divergence between conceptualization and technical feasibility was mitigated, although a considerable share of the software artifacts implemented at an early stage was discarded in the final implementation. The latter was achieved solely using freely available, open source software. Based on the gained practical experience, the compatibility between Design Science Research and typical software development workflow as outlined by ADIKARI et al. is confirmed [ADIK09]. This reflects in the use of GitLab™ Continuous Integration and Deployment as automated tool chain to expose the results of the design cycle to the reference system and applications at the M.A.R.S. laboratory.

HEVNER et al. also highlight the importance of result dissemination to different audiences [HEVN10, pp. 19-21]. Scientific dissemination has been achieved in form of multiple journal and conference proceedings contributions, while technical discussions were undertaken in consortia of the *Large Volume Applications (LaVA)* and *Internet of Production (IoP)* research projects. Presentations to management-affiliated audiences were conducted using the main application interface shown in Section 7.4. Within the research group, the CaaS development sustainably has contributed to the knowledge base: The system architecture and adhering IT infrastructure are being adopted by other applications at the time of writing, the same holds for multiple aspects of interface design. Time and effort to integrate Large-Scale Metrology instruments into experimental setups for other research projects have been significantly reduced by the availability of a CaaS system.

Critically reflecting the exposition to the application domain and assessment of impact, a comprehensive instantiation of CaaS in an industrial environment and its incorporation into a productive use case are still outstanding. In this regard, the benefits of CaaS over mostly commercial software applications for portable 3D metrology in practice should be reevaluated. The same holds for the effective reduction of implementation overhead through the servitized approach as the complexity of implementation for the application itself may become overruling or the physical integration of the necessary mobile entities may effectively impede the interchangeability of LSM instruments. Recapitulating the efforts in architecture design and protocol-agnostic interface definition, the industrial impact may be increased through a closer alignment with OPC UA, its respective architecture concept and notion of Companion Specifications (cf. Appendix K).

8.2 Technological Enablement and Recommendations

With CaaS, the provisioning of a virtual reference coordinate frame based on multiple, heterogeneous Large-Scale Metrology instruments is introduced. Therewith it acts as enabler to all applications requiring such a reference, e.g. metrology assisted assembly systems. More general, it provides the sensing ability for spatial synchronization between real world and virtual representation in Cyber-Physical Production Systems. The use of multiple, heterogeneous instruments facilitates to overcome technological limits of the individual instruments and is the foundation to incorporate economic benefits of adapting the instrument used to the requirements of a task, e.g. enabling the use of non-traceable, low cost systems in scenarios where the uncertainty contribution is not critical.

Recovering the motivation of increasing tolerance demands, product scales and manufacturing respectively assembly systems' volatility, the aerospace industry stands out where especially the assembly of large-scale aircraft structures represents the aforementioned characteristics. Metrology-assisted, flexible assembly concepts involving mobilization of product and resources have been actively developed in this field, which exemplarily reflects in patents held by The Boeing Company focusing on the use case of automated fuselage assembly for which Figure 8.1 shows two principal schematics [SARH10, OBER16]. In an illustrative example, mobile robotic machines are configured and subsequently moved to perform drilling or fastener installation to assemble the individual panels of a fuselage structure. The shop floor remains practically freely configurable. Metrological feedback in form of position information from one or multiple sources is an explicit part of the approach, while its technical materialization is not further specified. Hence, CaaS is able to provide an essential building block towards the successful implementation of such systems and is regarded as an enabler for future assembly systems relying on ubiquitous metrology [BERG20, pp. 158-180]. A major reason for the necessity of position information as reference is the use of mobile manipulators which need to be referenced towards the product respectively to each other.

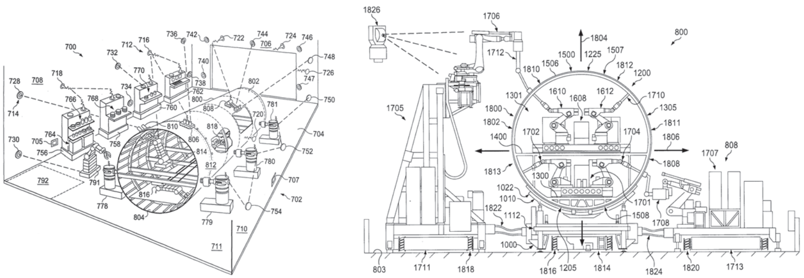

Figure 8.1: Schematic overviews of the technologies for flexible assembly described in the patents »Autonomous robotic assembly system comprising a plurality of mobile robotic machines and a wireless communication system« (left, [SARH10, p. 1]) and »Metrology-based system for operating a flexible manufacturing system« (right, [OBER16, p. 131]) developed in the context of the assembly of aircraft structures and held by The Boeing Company.

Figure 8.2: Left: Mobile robot platform for (collaborative) drilling, riveting and sealing applications developed by Broetje Automation GmbH for flexible automation systems in aerospace [Eick20]. **Right:** Large-scale kinematic consisting of gantry and robot for automated manufacturing operations on large, demanding work pieces developed within the MEGAROB project. To achieve the required kinematic accuracy, closed-loop control using a metrological reference, in this specific case a laster tracker, is implemented [AITI15].

Their advances, as exemplarily shown in Figure 8.2, pose another key enabler and their application is also discussed in other domains involving large-scale products, e.g. ship building as part of the maritime sector [Eick20]. Consequently, CaaS can contribute as metrological reference frame for scenarios in these domains and similar for *Line-less Mobile Assembly Systems (LMAS)* in general, too.

Another approach benefiting from CaaS, which has been motivated, is the improvement of volumetric performance, especially for large-scale kinematics. The use of alternative, e.g. robot based, platforms instead of extensive platforms based on large-volume machine tools offers great potential for cost reduction and flexibility gains. Figure 8.2 shows a combination of a large gantry and an articulating robot realized within the framework of the MEGAROB project [AITI15]. The effective tool center point is referenced using a laser tracker and due to its robotic nature, the platform can be used for a variety of processes, e.g. milling and drilling [AITI15]. An opportunity provided by CaaS is to extend this principle to multiple kinematics across the entire shop floor, i.e. also mobile manipulators, and to seamlessly exchange the metrological reference used for closed-loop control according to availability and requirements. The resulting use cases are relevant to large-scale products, e.g. processing components of aircrafts, wind energy systems, large turbines or maritime engines.

In general, the servitized approach enables arbitrary applications to incorporate Large-Scale Metrology in a coordinate system with global context over a defined interface. The ubiquitous availability of coordinate measurements endorses the transition from the local need for a coordinate measurement system to implement a distinct application to the notion of coordinate measurement ability as part of the shop floor’s infrastructure. As an example, the entry barrier to evaluation and implementation of in-line or at least near-line measurement strategies for intermediate dimensional checks in high value manufacturing can be significantly lowered by this approach. The infrastructural approach also endorses the integration with navigation systems of autonomously guided vehicles, which emerge to backbones of modern factories, e.g. in the automotive industry [ITEM19].

The instantiation of a complete CaaS system is regarded of very little use if the need for a metrological reference is a priori limited to a single application within a fixed subvolume on the shop floor. However, the elaborated abstracted interface to individual Large-Scale Metrology instruments may still be beneficial to reduce software engineering overhead when implementing the application or changing the instrument used. In addition, the artifact-free coordinate registration method developed can be used regardless of CaaS, e.g. to register the coordinate systems of a robot and an external LSM instrument.

The IT infrastructure to be implemented with a CaaS system should not be regarded exclusive to the latter, as its availability facilitates the general integration of distributed sensors and other services. Recovering the explicit implementation accompanying the CaaS demonstrator system, the close link to technologies and software also prevailing in the fields of Internet of Things and consumer internet endorses improved development times and human machine interaction. For future developments, the integration with other reference architectures and platform offerings (cf. Table 2.2) should be continuously evaluated.

8.3 Further Research Potential

Based on the advances achieved through the development of CaaS, further subsequent research topics emerge. An integration of CaaS into the implementation of a complex metrology assisted assembly scenario, liaised to a holistic analysis of resource management approaches including superordinate operations research is required to substantially evaluate the benefit of a servitized virtual reference frame in this application context.

In this context, refined virtual models of Large-Scale Metrology instruments would be beneficial as exemplarily apparent for the indoor GPS system. These would not only allow a better predictions of coverage, angular acceptance and covariance but also facilitate the development of strategies for layout optimizations for distributed systems or an entire CaaS setup. Outside the scope of CaaS, these models would also improve the model-based estimation of the instruments' contribution to the measurement uncertainty.

Moreover, the transfer of the servitization approach taken for Large-Scale Coordinate Metrology to other types of measurands should be investigated. This interest has been reflected by other researchers during the elaboration of CaaS and manifests in the importance of metrology and sensors in the *Internet of Production*. Herein a consolidation of the dual digital traceability proposal can be included, which requires the involvement of larger community to achieve an ample acceptance. Furthermore, a more explicit integration of CaaS with the concepts of RAMI 4.0 and the asset administration shell could be considered. The functional model developed in Chapter 4 and resource model elaborated in Chapter 6 can serve as the basis of a digital representation within the latter. The dissection into microservices in Chapter 5 facilitates the projection of CaaS to the layered RAMI 4.0 model, although still requiring an evaluation of audiences to expand the classification along all axes. A draft projection of CaaS' scope is visualized in Appendix J.

A further research idea emanating from CaaS is a domain-specific language to facilitate the applications relying on distributed, heterogeneous and servitized sensor data with integrated strategies for data integrity validation. It is motivated by the prevailing need to manually implement the aforementioned applications, even if the effort is already reduced through the servitized approach. Implementation efficiency, built-in documentation of data paths, algorithms and control-loops as well as reduced error proneness are the main benefits being envisaged. This idea aligns with the potential generalization of the servitization concept to other physical quantities and sensors, which has been recently introduced under the term of *Distributed Sensor Services* [PETE20, BERG20, pp. 158-180].

Glossary and Abbreviations

Advanced Message Queuing Protocol (AMQP)

cf. Section 4.1.

Application Programming Interface (API)

Interface a software system offers for automated interaction with other software; Ambigious in the context of Large-Scale Metrology as short name of Automated Precision Inc., a manufacturer of laser trackers.

Binary JSON (BSON)

Binary serialization scheme for different data types which is more efficient in terms of space as its text-based counterpart JSON.

Bluetooth Low Energy (BLE)

Network technology designed for energy-constrained devices defined in the Bluetooth 4.0 specification.

Central Limit Theorem

Theorem stating that a sum of independent random variables tends to a normal distribution even if the individual variables are not normally distributed.

Computer Aided Design (CAD)

Design utilizing assistance of computer-based systems and dedicated software including the generation of technical drawings.

Constrained Application Protocol (CoAP)

cf. Section 4.1.

Coordinate Measuring Machine (CMM)

cf. Section 2.1.

Cyber-Physical Production Systems (CPPS)

Cyber-Physical Systems are systems relating computing entities with a strong relation to the physical world, among others to leverage virtual models for real world applications. CPPS are a subclass dedicated to the domain of production engineering..

Digital Calibration Certificate (DCC)

cf. Section 4.3.

Everything as a Service (XaaS)

cf. Section 2.2.

Extensible Markup Language (XML)

Markup language for machine-readable, text-based data representation.

Geometric Dimensioning and Tolerancing (GD&T)

Discipline of defining and communicating toleraces for geometric features in engineering.

gRPC Remote Procedure Calls (gRPC)

cf. Section 4.1.

Guide to the Expression of Uncertainty in Meausrement (GUM)

Standardized (ISO/IEC Guide 98-3:2008-09) document with guidelines to expressing and propagating measurement uncertainty.

Hyptertext Transfer Protocol (HTTP)

Stateless communication protocol nowadays building the basis of the world wide web.

Infrastructure as a Services (IaaS)

cf. Section 2.2.

Internet of Things (IoT)

Shallow defined concept of widely interconnected assets in form of sensors, actors, computing platforms and user interaction devices.

JavaScript Object Notation (JSON)

Lightweight, text-based serialization scheme for different datatypes.

Large-Scale Metrology (LSM)

cf. Section 2.1.

Line-less Mobile Assembly System (LMAS)

Novel assembly paradigm introduced by SCHMITT et al. implying a clean shop floor, unrestricted assignment and full mobility of all resources, cf. Section 1.1.

M.A.R.S.

Acronym for Metrology, Assembly and Robotic Systems, and name of the laboratory shop floor of the author's affiliation.

Message Queuing Telemetry Transport (MQTT)

cf. Section 4.1.

National Metrology Institute (NMI)

Institution acting as national authority for questions of legal metrology.

OAuth2

Standardized protocol for authorization of web based APIs.

Open Platform Communications Unified Architecture (OPC UA)

cf. Section 4.1.

OpenID Connect

Protocol built on top of OAuth2 to include authentication in single-sign-on systems.

Platform as a Service (PaaS)

cf. Section 2.2.

Position Calculation Engine (PCE)

Mobile entity type used by the Nikon indoor GPS™ system.

Programmable Logic Controller (PLC)

Ruggedized computer system optimized for the use in industrial control loops with dedicated reliability and timing requirements.

Representational State Transfer (REST)

cf. Section 4.1.

Reverse Proxy

Server provisioning resources from different backend servers to a consumer as a single point of contact.

SHA-256

Member of the Secure Hash Algorithm family developed by NIST and widely used in information technology.

Software as a Service (SaaS)

cf. Section 2.2.

Software Development Kit (SDK)

Collection of tools and/or libraries bundled to facilitate the development of software in a specific context (e.g. for a specific device).

Spherically Mounted Retroreflector (SMR)

Target type frequently used in optical system consisting of a hollow corner cube reflector mounted in a sphere of known diameter.

Ultrawideband (UWB)

Communication using a band of at least 500 Hz between 3.1 GHz and 10.6 GHz.

Uniform Resource Locator (URL)

Subtype of uniform resource identifiers commonly used in the context of HTTP and the world wide web.

Universally Unique Identifier (UUID)

Unique identifier type in information technology, typically 128 bit long and based on random seeds leading to very low duplication probability even for distributed generation.

WZL

Laboratory for Machine Tools and Production Engineering WZL at RWTH Aachen University; Short name of the research institute the author is affiliated with.

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Matthias Bodenbenner:
Development of a Camera-based Tracking Theodolite
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Figure 2.3 represents joint work in the context of this thesis.

Dejan Boberic:
Generic IoT Gateway Architecture Concept Based on Analysis of IoT Communication Patterns
Master Thesis, 2018
Figure 4.2 represents joint work in the context of this thesis.

Thorsten Krüger:
Systematische Weiterentwicklung eines optischen Multisensors zur strukturintegrierten Kalibrierung von Werkzeugmaschinen
Bachelor Thesis, 2018

Merle Sophie Losch:
Optimization of cellular detection and tissue classification in digital pathology
Bachelor Thesis, 2018

Marvin Berthold:
Implementierung einer flexiblen Kompensationsschnittstelle für die Steuerung einer Portalfräsmaschine
Bachelor Thesis, 2017

Marvin Berthold:
Entwicklung einer dynamischen Programmbibliothek zur Ansteuerung eines interferometrischen Messgerätes über TCP/IP und JSON-RPC zur Verwendung in Forschungsprojekten
Seminar Thesis, 2016

Appendix

A Additional Coordinate Registration Results

$\mathcal{P}_i$	Run 001	Run 002	Run 003	Run 004	Run 005
a_i	0.142641 $\pm$ 0.000012	0.142695 $\pm$ 0.000014	0.142685 $\pm$ 0.000012	0.142726 $\pm$ 0.000011	0.142710 $\pm$ 0.000009
b_i	− 0.003745 $\pm$ 0.000016	− 0.003766 $\pm$ 0.000024	− 0.003772 $\pm$ 0.000012	− 0.003762 $\pm$ 0.000010	− 0.003782 $\pm$ 0.000009
c_i	− 0.003657 $\pm$ 0.000017	− 0.003752 $\pm$ 0.000010	− 0.003718 $\pm$ 0.000008	− 0.003715 $\pm$ 0.000011	− 0.003710 $\pm$ 0.000009
d_i	− 0.989723 $\pm$ 0.000010	− 0.989748 $\pm$ 0.000013	− 0.989728 $\pm$ 0.000009	− 0.989708 $\pm$ 0.000010	− 0.989703 $\pm$ 0.000004
$T_{x,i}$ [m]	3.740879 $\pm$ 0.000104	3.740835 $\pm$ 0.000126	3.740699 $\pm$ 0.000093	3.740419 $\pm$ 0.000097	3.740438 $\pm$ 0.000043
$T_{y,i}$ [m]	3.633033 $\pm$ 0.000073	3.633000 $\pm$ 0.000113	3.633006 $\pm$ 0.000066	3.633358 $\pm$ 0.000064	3.633159 $\pm$ 0.000053
$T_{z,i}$ [m]	− 1.607044 $\pm$ 0.000136	− 1.607449 $\pm$ 0.000165	− 1.607547 $\pm$ 0.000117	− 1.607299 $\pm$ 0.000093	− 1.607296 $\pm$ 0.000057
l [m]	0.562135 $\pm$ 0.000039	0.562325 $\pm$ 0.000049	0.562125 $\pm$ 0.000017	0.562068 $\pm$ 0.000023	0.562117 $\pm$ 0.000014
$\mathcal{W}^*$ [m]	2.09, 1.28, 1.37	1.30, 2.04, 1.28	2.57, 1.57, 1.99	3.15, 2.25, 1.57	2.56, 2.26, 1.83
$n_{locations}$	50	26	65	67	70
χ^2/NDF	6.40	5.40	6.34	9.44	8.68

Table A.1: Overview of $\mathcal{P}_i^{opt}$ for another measurement campaign for coordinate registration among laser tracker and indoor GPS similar to the one summarized in Table 3.1. The results slightly differ and χ^2/NDF tends to be higher. It is assumed that this is a result of a reduced quality of the indoor GPS calibration on that specific day.

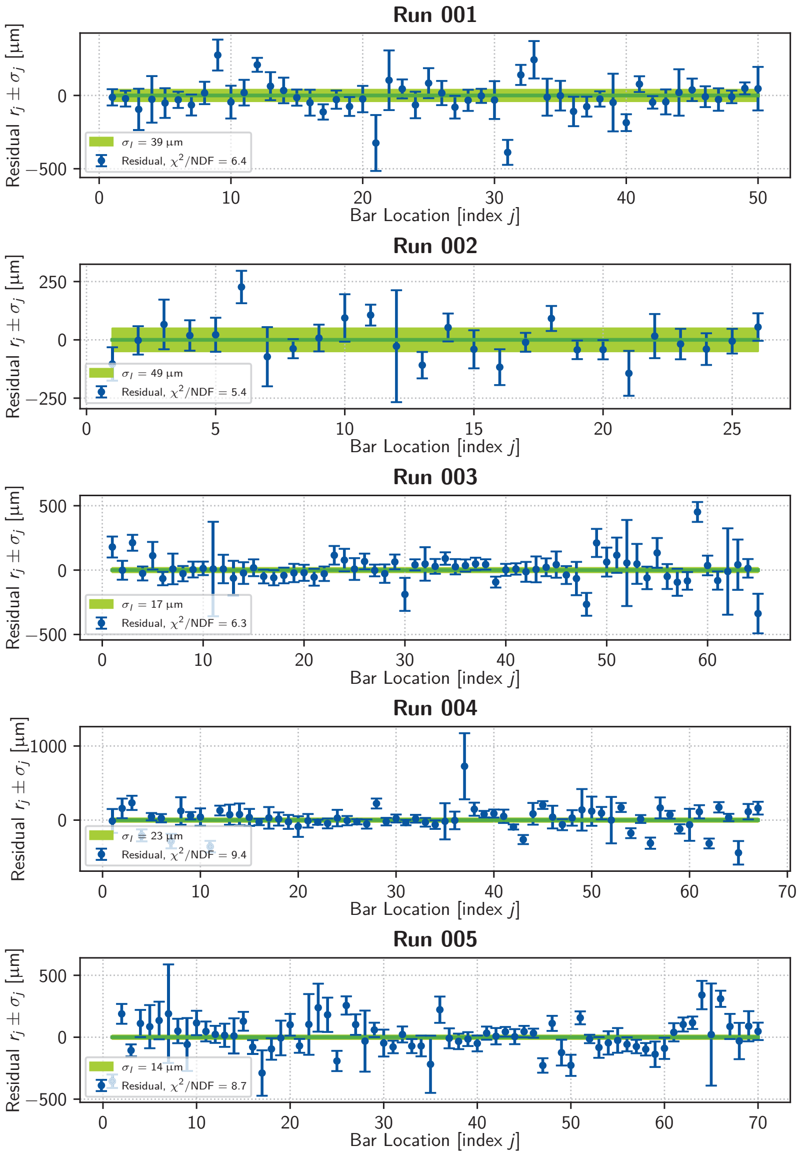


Figure A.1: Residuals of the five measurement runs for a coordinate registration between Nikon iGPS™ and API Radian™ with results denoted in Table A.1. The light green area corresponds to the estimated parameter uncertainty of l, while r_j and σ_j are computed according to eqs. (3.16) and (3.22) for the obtained parameters and plotted with error bars.

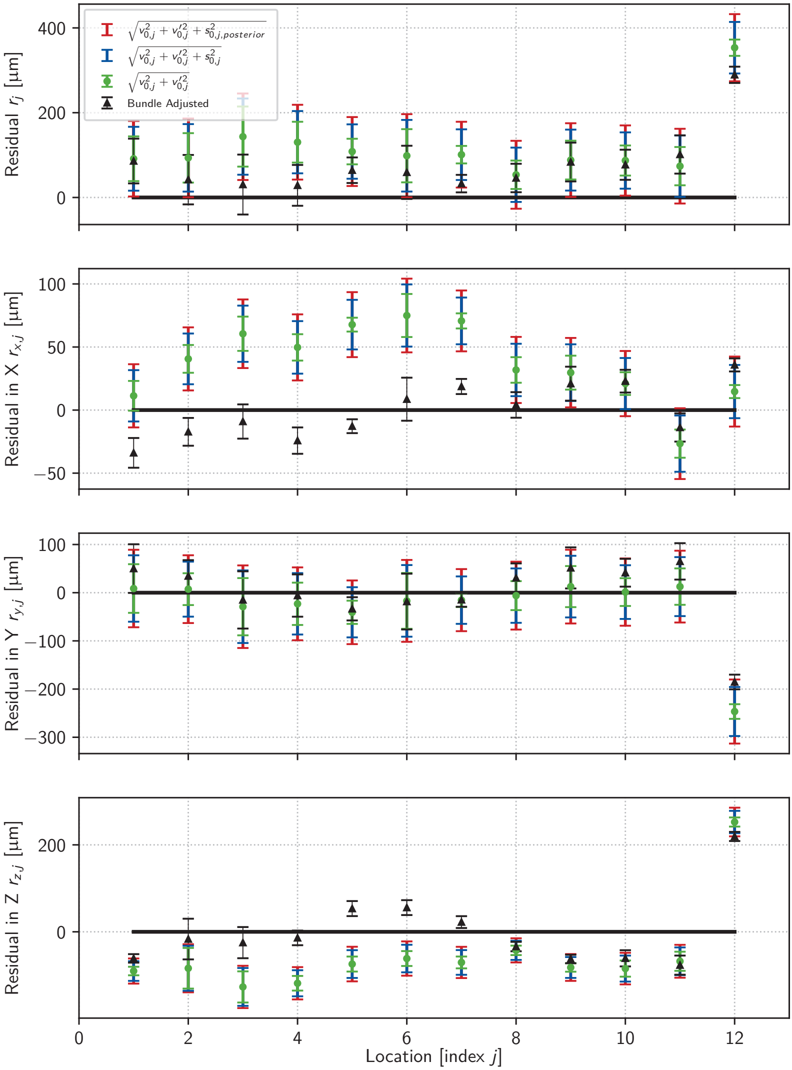


Figure A.2: Details of residuals shown in Figure 3.7 where the contributions along each axis are shown.

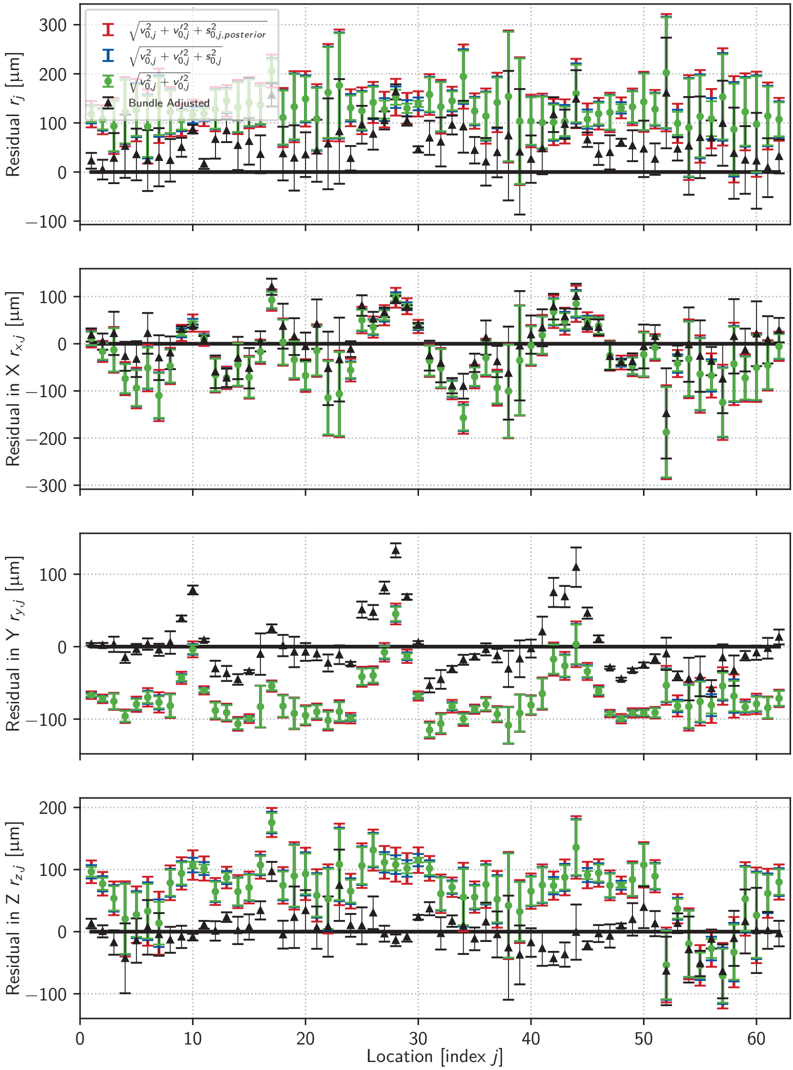


Figure A.3: Detailed representation of the residuals for the repetition of the measurement campaign to align to API Radian™ laser trackers using the novel method and a larger set of common SMR locations. The results of this campaign show that under certain circumstances, the method may be susceptible to systematic errors, as especially the residuals in Y and Z direction show an offset compared to the results of a bundle adjustment.

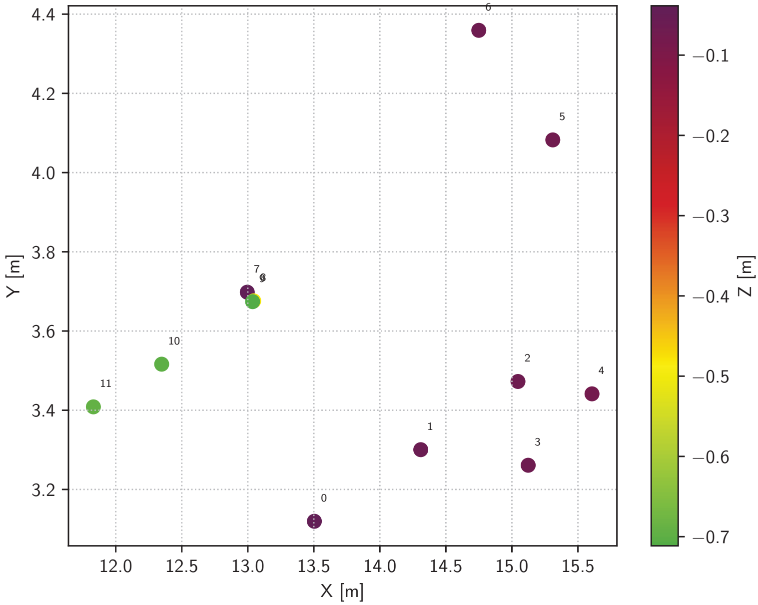


Figure A.4: Reference location used for the coordinate registration validation campaign using two API Radian™laser trackers. The positions are expressed in the native coordinate system of the first laser tracker, to which the coordinate system of the second was registered.

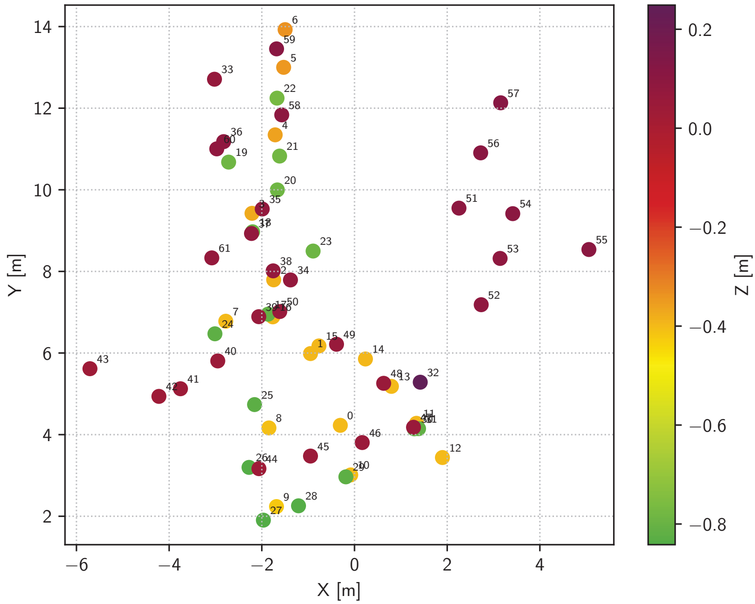


Figure A.5: Reference location used for the repeated coordinate registration validation campaign using two API Radian™laser trackers. The positions are expressed in the native coordinate system of the first laser tracker, to which the coordinate system of the second was registered.

$\mathcal{P}_i$	Coordinate Registration 001	Bundle Adjustment 001	Coordinate Registration 002	Bundle Adjustment 002
a_i	0.006396 $\pm$ 0.000002	0.006415	0.0004039 $\pm$ 0.0000009	0.0004111
b_i	-0.526473 $\pm$ 0.000001	-0.526472	0.4940658 $\pm$ 0.0000004	0.4940692
c_i	-0.850155 $\pm$ 0.000002	-0.850167	-0.8694182 $\pm$ 0.0000006	-0.8694167
d_i	0.001390 $\pm$ 0.000004	0.001404	-0.0031760 $\pm$ 0.0000007	-0.0031754
$T_{x,i}$ [m]	10.743813 $\pm$ 0.000024	10.743947	2.3453602 $\pm$ 0.0000058	2.3454216
$T_{y,i}$ [m]	1.429570 $\pm$ 0.000053	1.429472	0.3199811 $\pm$ 0.0000063	0.3199545
$T_{z,i}$ [m]	2.601835 $\pm$ 0.000025	2.601992	2.7768158 $\pm$ 0.0000098	2.7769017
l [m]	0.229432 $\pm$ 0.000052	-	0.2294889 $\pm$ 0.0000053	-
$n_{locations}$	81	12	113	62
χ^2/NDF	1.78	-	5.48	-

Table A.2: Overview of $\mathcal{P}_i^{\text{opt}}$ and coordinate transformation obtained using bundle adjustment for the validation campaign (001) and its repetition (002) using two API Radian™ laser trackers. The parameters obtained for the bundle adjustment are stated without uncertainty as a plain, unweighted approach without propagation of uncertainties was chosen. Especially for the second campaign, the high value of χ^2/NDF, small parameter uncertainties and hence disagreement between novel approach and plain bundle adjustment indicate unmodeled systematic effects to which the novel method may be susceptible.

B Evaluated Instrument Model Query

```
POST metrology.wzl.rwth-aachen.de/mars-backend/entities/interface/
     {"positions": [[4,5,2], [4.1, 4.9, 1]]}
```


```
{
    "key": "8800405b-eb41-4ab7-8404-c34071a9b4d2",
    "environment": {
        "uuid": "d879aac1-76a8-493d-b73d-84573f487293",
        "name": "Default",
        "T": [18.0, 25.0],
        "p": [93000.0,110000.0],
        "H": [0.05,0.95]
    },
    "instrument": "radian-e7ccdff2-764d-42b2-91af-4dd52f9187e6",
    "uuid": "OBJ-HOMESMR",
    "name": "Default SMR",
    "active": false,
    "B": [true, true],
    "Q": [true, false],
    "V": [
          [[2.394043e-10, 1.795555e-10, 7.182222e-11],
           [1.795555e-10, 1.445555e-10, 2.222222e-13],
           [7.182222e-11, 2.222222e-13, 3.690888e-10]],
          [[2.201982e-10, 1.803299e-10, 3.680196e-11],
           [1.803296e-10, 1.518641e-10, 1.171688e-13],
           [3.680194e-11, 1.171688e-13, 3.674039e-10]]
         ],
    "t_measure": 0.001,
    "t_dead": 0.01,
    "f_sample": 1000.0,
    "v_max": 10.0,
    "O": false,
    "F": "REFLECTOR",
    "R": true,
    "T": true,
    "K": true,
    "Z": false,
        "siblings": []
}
```


Figure B.1: JSON serialization of entity information after evaluation of the instrument model as is done internally by the planning microservice.

C Additional Interface Details

FUN-Reset ($\emptyset \rightarrow \emptyset$)
Reset or boot the entire system.
PAR-State ($\emptyset \rightarrow \emptyset$)
Shut down the entire system.
PAR-State (enum {OK, WARNING, ERROR, MAINTENANCE})
Reflects the state of the entire system.
PAR-Manufacturer (string)
Identifier of the system's manufacturer.
PAR-Version (int)
Incremental interface version.
PAR-Time (time)
Current system time.

Table C.1: Descriptions of interface elements of the Generic Device Type.

FUN-Covariance (id[n] $\rightarrow$ double[n,n])
Return the covariance matrix ($n \times n$) of n variables according to the passed identifiers. The data type of the identifier depends on the specific protocol.
PAR-Calibration (string)
String-based identifier unambiguously related to calibration certificate of the instrument.

Table C.2: Descriptions of interface elements of the root Large-Scale Metrology Object Type.

D Python-Style Sample Code for CaaS Consumption

Python

```python
import getpass
from keycloak import KeycloakOpenID
import requests
import numpy
import json

CLIENT_ID = ""
CLIENT_SECRET =""
USER = ""
URL = "https://metrology.wzl.rwth-aachen.de/"

try:
    openID_client = KeycloakOpenID(
        server_url=URL + "auth/",
        client_id=CLIENT_ID,
        realm_name="metrology",
        client_secret_key=CLIENT_SECRET
    )

    token = openID_client.token(
        USER,
        getpass.getpass("Please enter password:")
    )

    headers = {
        "Content-Type" : "application/json",
        "Authorization" : "Bearer {}".format(token["access_token"])
    }

    start_time = "2020-07-21T12:00:00.0Z"
    end_time = "2020-07-21T15:00:00.0Z"
    reference_positions = [
        [7.0, 7.0, 0.5], [7.0, 8.0, 0.5],
        [8.0, 7.0, 0.5], [8.0, 8.0, 0.5]
        ]

    entities = requests.post(
        URL + "entities/entities/?start={}&end={}&rank={}".format(
            start_time, end_time, True
            ),
        json={"positions" : reference_positions},
        headers=headers
    ).json()

    entity = None
    for i, e in enumerate(entities):
```

```
        B = numpy.array(e["B"])
        if B.all():
            covariance = numpy.array(e["V"]) + numpy.array(e["S"])
            U = numpy.sqrt(
                numpy.sum(
                    covariance.diagonal(axis1=1, axis2=2),
                    axis=1)
            )

            if (U<0.005).all():
                entity = e
                break
    if entity is None:
        raise RuntimeError("No suitable entity found!")

    allocation = requests.post(
        URL + "entities/allocations/",
        json={
            "entity" : entity["key"],
            "level" : "USE",
            "starts_at" : start_time,
            "ends_at" : end_time,
            "user" : USER
        },
        headers=headers
    ).json()

    instrument = requests.get(
        URL + "entities/instruments/{}".format(entity["instrument"]),
        headers=headers
    ).json()

    thing = requests.get(
        URL + "things/{}".format(instrument["thing_id"]),
        headers=headers
    ).json()

    thing_headers = {
        "Content-Type" : "application/json",
        "Authorization" : "Bearer {}".format(allocation["key"])}

    requests.put(
        thing["url"] + "OBJ-LSMSystem/OBJ-Entities/"
        "{}/PAR-State".format(entity["uuid"]),
        {"value" : "CONTINUOUS"},
        headers = thing_headers
    )

    result = requests.get(thing["url"] + "OBJ-LSMSystem/OBJ-Entities/"
    "{}/VAR-Position".format(entity["uuid"])).json()

    print("=== {} ===".format(result["timestamp"]))
```

```
    print("Position                   Covariance")
    print(
        "                           {:.6f} {:.6f} {:.6f}"
        .format(*result["covariance"][0])
    )
    print(
        "{:.6f}, {:.6f}, {:.6f} m   {:.6f} {:.6f} {:.6f} [m^2]"
        .format(*result["value"], *result["covariance"][1])
    )
    print(
        "                           {:.6f} {:.6f} {:.6f}"
        .format(*result["covariance"][2])
        )
    print("")
    print("=== Transformation ===")
    print(json.dumps(instrument["transformation"], indent=4))

except Exception as exception:
    print("[ERROR] {}".format(exception))
```

E Instrument Model Details

The models both used for the allocation metric study and instrument modeling microservices in the CaaS demonstrator setup are described in further detail for laser tracker and indoor GPS. The constant uncertainty and visibility models used for the Pozyx UWB system ($\sigma_{Pozyx} = 5\,\text{mm}$) and calibrated machine tool ($\sigma_{MT} = 15\,\mu\text{m}$) are not explained in further detail due to their simplicity.

The virtual shop floor mimics a setup similar to the setup in the M.A.R.S. laboratory. It has a volume of $20\,\text{m} \times 40\,\text{m} \times 5\,\text{m}$. Three laser trackers and an indoor GPS system are configured as further explained in the following Sections. The coverage of the indoor GPS is additionally constrained to the first half ($y \in [0, 20]$ m) to replicate typical visibility limits. The coverage of the UWB system spans the entire shop floor. In the virtual setup, a machine tool of $1.5\,\text{m} \times 2.0\,\text{m} \times 0.5\,\text{m}$ working volume is located at $(4.0, 35.0, 0.0)$ m[1].

Laser Tracker

For the laser tracker model introduced in eqs. (7.1)-(7.3), the values denoted hereunder have been used. They follow the standard deviation coefficients of the results of HUGHES et al. and are assumed to be typical for laser trackers [HUGH11, p. 17]. The acceptance angle of ±25° is typical to SMRs and a full range for azimuth and elevation has been allowed. Figure E.1 shows two representations of the resulting covariance model $\hat{\mathbf{V}}$.

$$
\begin{aligned}
\sigma_{r,0} &= 1.216\,\mu\text{m} \\
\sigma_{r,1} &= 1.517\,\frac{\mu\text{m}}{\text{m}} \\
\sigma_{\varphi,0} &= 2.351\,\mu\text{rad} \\
\sigma_{\varphi,1} &= 2.351\,\mu\text{rad} \cdot \text{m} \\
\sigma_{\theta,0} &= 3.365\,\mu\text{rad} \\
\sigma_{\theta,1} &= 3.365\,\mu\text{rad} \cdot \text{m} \\
R_{valid} &= [0.2\,\text{m}, 20.0\,\text{m}] \\
\Phi_{valid} &= [-360^\circ, 360^\circ] \\
\Theta_{valid} &= [-90^\circ, 90^\circ] \\
\sphericalangle_{acceptance} &= 25^\circ
\end{aligned}
$$

[1] The origin of the machine tool has been lowered to allow for more elucidating studies in the $z = 0$ plane.

The models are evaluated with respect to the origin of the laser tracker. For the virtual shop floor, the following locations were used:

$$\text{Origin}_1 = \begin{pmatrix} 0.0 \\ 0.0 \\ 1.5 \end{pmatrix}$$

$$\text{Origin}_2 = \begin{pmatrix} 7.0 \\ 17.5 \\ 5.0 \end{pmatrix}$$

$$\text{Origin}_3 = \begin{pmatrix} 20.0 \\ 20.0 \\ 2.0 \end{pmatrix}$$

Indoor GPS

The setup of the indoor GPS system on the virtual shop floor follows an actual setup temporarily used in the M.A.R.S. laboratory. Different rotations have been omitted as they are not expected to have a major impact on the uncertainty model due to the rotational symmetry of the transmitters and their typical upright position. The following parameters are used for the model denoted in eq. (7.4):

$$\tilde{T}_1 = \begin{pmatrix} 9.175 \\ 0.911 \\ 4.826 \end{pmatrix} \text{m} \qquad \tilde{\mathbf{R}}_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\tilde{T}_2 = \begin{pmatrix} 11.253 \\ 7.712 \\ 1.881 \end{pmatrix} \text{m} \qquad \tilde{\mathbf{R}}_2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\tilde{T}_3 = \begin{pmatrix} 4.444 \\ 7.436 \\ 1.923 \end{pmatrix} \text{m} \qquad \tilde{\mathbf{R}}_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\tilde{T}_4 = \begin{pmatrix} 0.052 \\ 16.697 \\ 4.293 \end{pmatrix} \text{m} \qquad \tilde{\mathbf{R}}_4 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\tilde{T}_5 = \begin{pmatrix} 4.427 \\ 15.680 \\ 1.930 \end{pmatrix} \text{m} \qquad \tilde{\mathbf{R}}_5 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\tilde{T}_6 = \begin{pmatrix} 9.453 \\ 16.706 \\ 4.256 \end{pmatrix} \text{m} \qquad \tilde{\mathbf{R}}_6 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

For the uncertainty coefficients, the assumptions reported by HUGHES et al. are used [HUGH10, pp. 4-6]:

$$\begin{aligned} \sigma_{\varphi,0} = \sigma_{\theta,0} &= 4.848\ \mu\text{rad} \\ \sigma_{\varphi,1} = \sigma_{\theta,1} &= 100\ \mu\text{rad} \cdot \text{m} \\ \sphericalangle_{acceptance} &= 90^\circ \end{aligned}$$

Figure E.2 shows two representations of the resulting covariance model $\hat{\mathbf{V}}$.

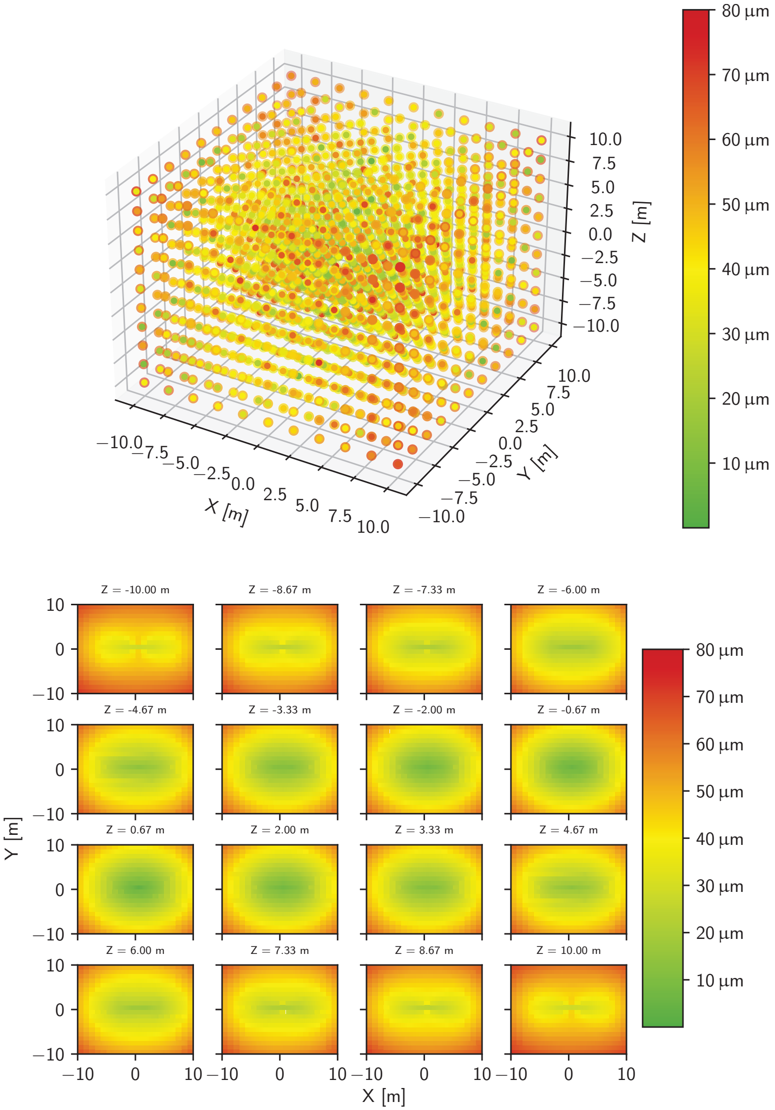


Figure E.1: Color-coded 2D and 3D view of laser tracker uncertainty model as defined in eq. (7.1). The scalar simplification motivated in eq. (3.10) has been applied.

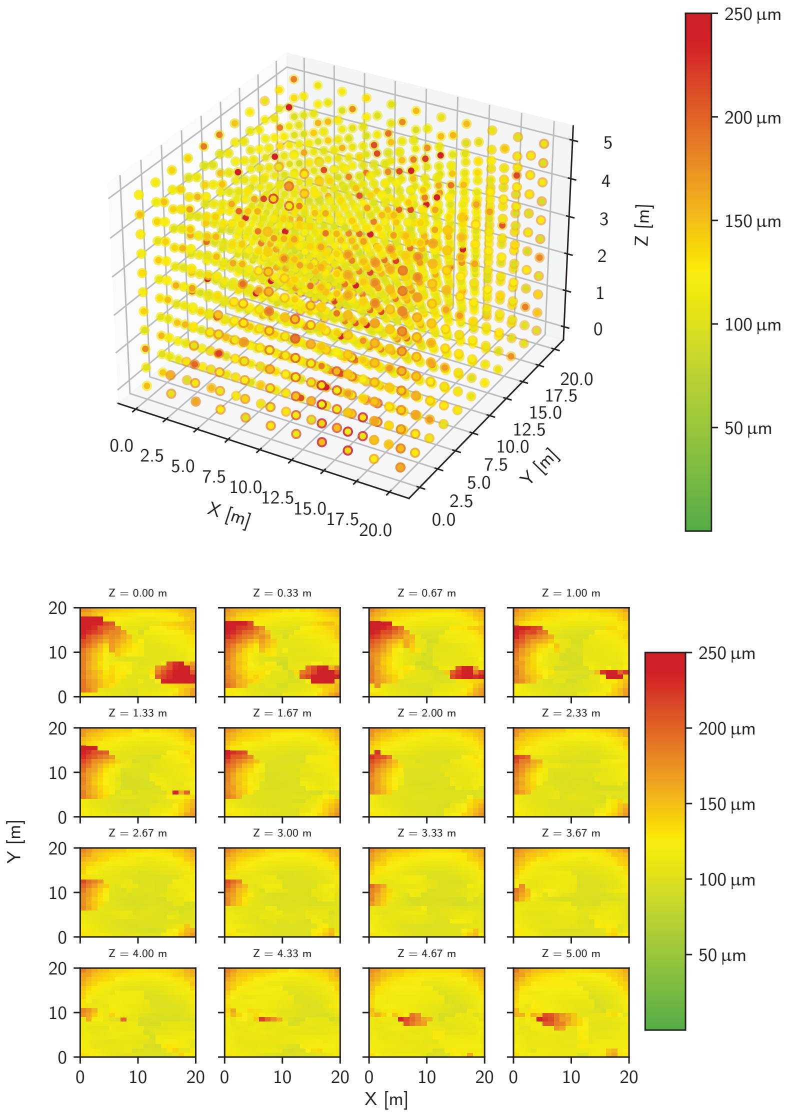


Figure E.2: Color-coded 2D and 3D view of indoor GPS uncertainty model as defined in eq. (7.4). The scalar simplification motivated in eq. (3.10) has been applied.

F Allocation Metric Study

The following tables detail the result of the simulation study carried out to evaluate the suitability of the Γ-ranked entity selection approach. For each series, 20 randomized requests are generated and evaluated in the same order by both algorithms. Generally insatiable requests are filtered out. In the tables, the index of the first denied request and the total number of accepted requests per ranking approach are denoted. Series where the ranked approach outperforms the random approach are highlighted in green, while the opposite outcome is highlighted in red.

Run	First Denial Ranked	First Denial Random	Success Ranked	Success Random	Total Requests
001	-	3	10/10	8/10	20
002	10	6	10/11	10/11	20
003	-	4	9/9	8/9	20
004	-	6	8/8	7/8	20
005	-	-	4/4	4/4	20
006	-	-	11/11	11/11	20
007	-	2	12/12	11/12	20
008	-	4	9/9	8/9	20
009	-	-	8/8	8/8	20
010	10	1	10/11	9/11	20
011	-	3	10/10	8/10	20
012	-	-	12/12	12/12	20
013	-	4	9/9	8/9	20
014	-	5	10/10	9/10	20
015	-	-	11/11	11/11	20
016	-	6	10/10	9/10	20
017	-	4	6/6	5/6	20
018	-	5	7/7	6/7	20
019	-	-	8/8	8/8	20
020	-	-	9/9	9/9	20
021	-	-	5/5	5/5	20
022	-	-	9/9	9/9	20
023	-	7	9/9	8/9	20
024	-	-	9/9	9/9	20
025	2	3	10/11	10/11	20

Table F.1: Detailed results of allocation metric study (001-025).

Run	First Denial Ranked	First Denial Random	Success Ranked	Success Random	Total Requests
026	-	-	9/9	9/9	20
027	-	2	9/9	7/9	20
028	-	-	11/11	11/11	20
029	-	-	11/11	11/11	20
030	-	3	10/10	8/10	20
031	-	4	8/8	7/8	20
032	-	6	10/10	9/10	20
033	-	-	7/7	7/7	20
034	-	-	10/10	10/10	20
035	11	7	11/12	11/12	20
036	9	5	9/10	9/10	20
037	-	9	10/10	9/10	20
038	3	4	10/12	10/12	20
039	-	-	11/11	11/11	20
040	-	2	7/7	6/7	20
041	-	2	9/9	8/9	20
042	-	-	8/8	8/8	20
043	-	6	10/10	9/10	20
044	-	4	9/9	8/9	20
045	-	2	8/8	7/8	20
046	3	7	11/12	11/12	20
047	-	2	10/10	9/10	20
048	-	-	10/10	10/10	20
049	9	7	10/11	10/11	20
050	-	2	10/10	9/10	20

Table F.2: Detailed results of allocation metric study (026-050).

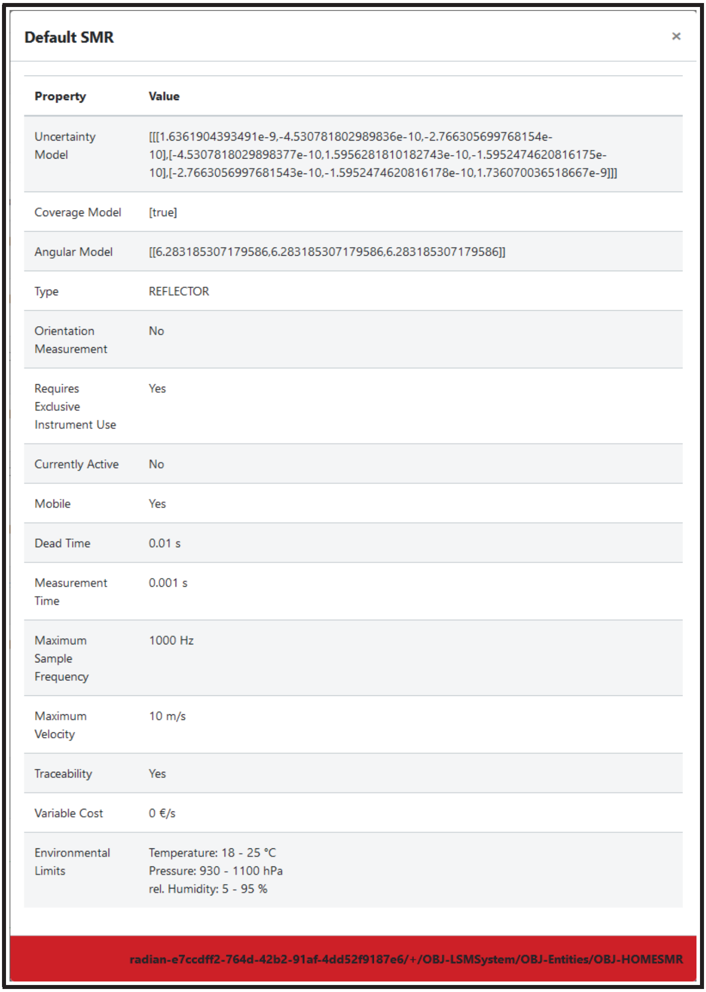
Run	First Denial Ranked	First Denial Random	Success Ranked	Success Random	Total Requests
051	4	2	8/9	8/9	20
052	-	-	10/10	10/10	20
053	-	-	8/8	8/8	20
054	12	7	12/13	12/13	20
055	-	2	11/11	9/11	20
056	-	-	11/11	11/11	20
057	-	4	7/7	6/7	20
058	-	-	11/11	11/11	20
059	-	8	9/9	8/9	20
060	-	-	6/6	6/6	20
061	8	4	9/11	9/11	20
062	1	2	10/11	10/11	20
063	6	-	6/7	7/7	20
064	-	-	8/8	8/8	20
065	12	6	12/13	11/13	20
066	-	-	9/9	9/9	20
067	-	7	8/8	7/8	20
068	-	4	11/11	10/11	20
069	-	-	7/7	7/7	20
070	9	3	10/11	10/11	20
071	-	6	10/10	9/10	20
072	-	6	9/9	8/9	20
073	-	-	5/5	5/5	20
074	-	3	9/9	8/9	20
075	9	4	9/10	8/10	20

Table F.3: Detailed results of allocation metric study (051-075).

Run	First Denial Ranked	First Denial Random	Success Ranked	Success Random	Total Requests
076	-	-	7/7	7/7	20
077	-	-	7/7	7/7	20
078	-	-	6/6	6/6	20
079	-	5	10/10	9/10	20
080	13	4	13/14	12/14	20
081	10	5	10/11	10/11	20
082	5	1	10/11	10/11	20
083	-	-	5/5	5/5	20
084	-	-	11/11	11/11	20
085	-	-	9/9	9/9	20
086	11	8	12/13	12/13	20
087	-	2	11/11	10/11	20
088	-	2	8/8	7/8	20
089	-	8	9/9	8/9	20
090	-	-	7/7	7/7	20
091	-	-	6/6	6/6	20
092	-	2	7/7	6/7	20
093	-	3	9/9	8/9	20
094	-	-	10/10	10/10	20
095	-	-	8/8	8/8	20
096	10	3	10/11	9/11	20
097	-	-	8/8	8/8	20
098	10	4	10/11	10/11	20
099	-	-	10/10	10/10	20
100	10	4	10/11	10/11	20

Table F.4: Detailed results of allocation metric study (076-100).

G User Interface Screenshots



Default SMR

Property	Value
Uncertainty Model	[[[1.6361904393491e-9,-4.530781802989836e-10,-2.766305699768154e-10],[-4.5307818029898377e-10,1.5956281810182743e-10,-1.5952474620816175e-10],[-2.7663056997681543e-10,-1.5952474620816178e-10,1.736070036518667e-9]]]
Coverage Model	[true]
Angular Model	[[6.283185307179586,6.283185307179586,6.283185307179586]]
Type	REFLECTOR
Orientation Measurement	No
Requires Exclusive Instrument Use	Yes
Currently Active	No
Mobile	Yes
Dead Time	0.01 s
Measurement Time	0.001 s
Maximum Sample Frequency	1000 Hz
Maximum Velocity	10 m/s
Traceability	Yes
Variable Cost	0 €/s
Environmental Limits	Temperature: 18 - 25 °C Pressure: 930 - 1100 hPa rel. Humidity: 5 - 95 %

radian-e7ccdff2-764d-42b2-91af-4dd52f9187e6/+/OBJ-LSMSystem/OBJ-Entities/OBJ-HOMESMR

Figure G.1: Human-readable representation of entity characteristics based on according queries to the microservice $\mathbb{E}$.

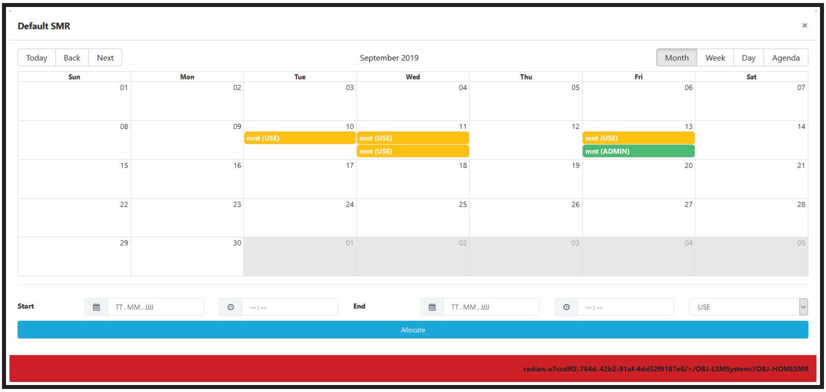


Figure G.2: Calendar view of the time-based allocation per entity as part of the CaaS reference user interface.

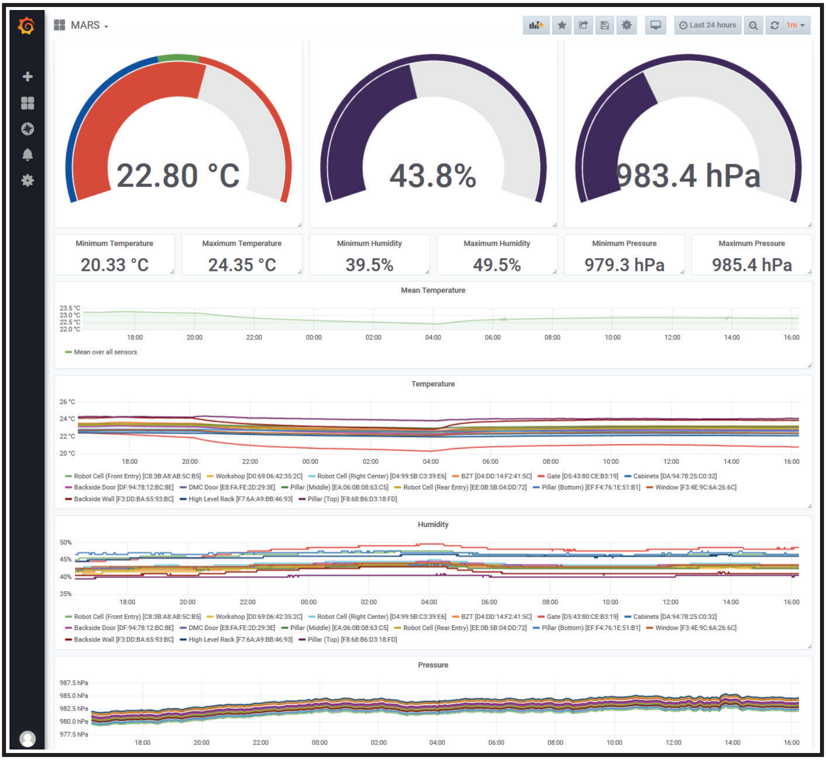


Figure G.3: Time-Series dashboard acting as frontend for the database microservice, exemplary showing data of the environmental sensors distributed across the laboratory shop floor.

H ROS Message Format

header	**std_msgs/Header.msg**
`uint32 seq`	consecutively increasing ID
`time stamp`	Two-integer timestamp (seconds, nanoseconds)
`string frame_id`	Frame this data is associated with
pose/position	**geometry_msgs/Point.msg**
`float64 x`	Corresponds to p_x, expressed in millimeters
`float64 y`	Corresponds to p_y, expressed in millimeters
`float64 z`	Corresponds to p_z, expressed in millimeters
pose/orientation	**geometry_msgs/Quaternion.msg**
`float64 x`	(Optional) orientation, 2nd quaternion component
`float64 y`	(Optional) orientation, 3rd quaternion component
`float64 z`	(Optional) orientation, 4th quaternion component
`float64 w`	(Optional) orientation, 1st quaternion component
pose/covariance	**–**
`float64[36] covariance`	Row-major representation of the 6x6 covariance matrix. The orientation parameters use a fixed-axis representation. In order, the parameters are: (x, y, z, rotation about X axis, rotation about Y axis, rotation about Z axis). The upper 3×3 block matrix corresponds to **V** expressed in millimeters (squared). Angular components are expressed in radians (squared).

Table H.1: Message definition and associated content of `geometry_msgs/PoseWithCovarianceStamped` used as native data type to expose position information of CaaS to the ROS domain.

translation	**geometry_msgs/Vector3.msg**
`float64 x`	Corresponds to $T_{x,i}$, expressed in millimeters
`float64 y`	Corresponds to $T_{y,i}$, expressed in millimeters
`float64 z`	Corresponds to $T_{z,i}$, expressed in millimeters
rotation	**geometry_msgs/Quaternion.msg**
`float64 x`	Corresponds to b_i
`float64 y`	Corresponds to c_i
`float64 z`	Corresponds to d_i
`float64 w`	Corresponds to a_i

Table H.2: Message definition and associated content of `geometry_msgs/Transform` used as native data type to expose coordinate transformations from CaaS to the ROS domain. Parameter uncertainties are not included in the native data type but can be added using a custom parent data type.

I Licenses of Used Software

Software/Package	License
Keycloak™	Apache License 2.0
MQTTnet	MIT License
django	BSD License
django-rest-framework	BSD License
Eclipse Paho	Eclipse Public License
InfluxDB	MIT License
Grafana®	Apache License 2.0
cpprestsdk	MIT License
asyncio	PSF License
numpy	PSF License
MINUIT	Public Domain
ROS	BSD License
ReactJS	MIT License
Node-RED	Apache License 2.0

Table I.1: Licenses of software used to implement the CaaS demonstrator system. All licenses are considered as open source variants. Some products are offered with extended functionality under a dual license, but none of them was used.

J Provisional Projection of CaaS to RAMI 4.0

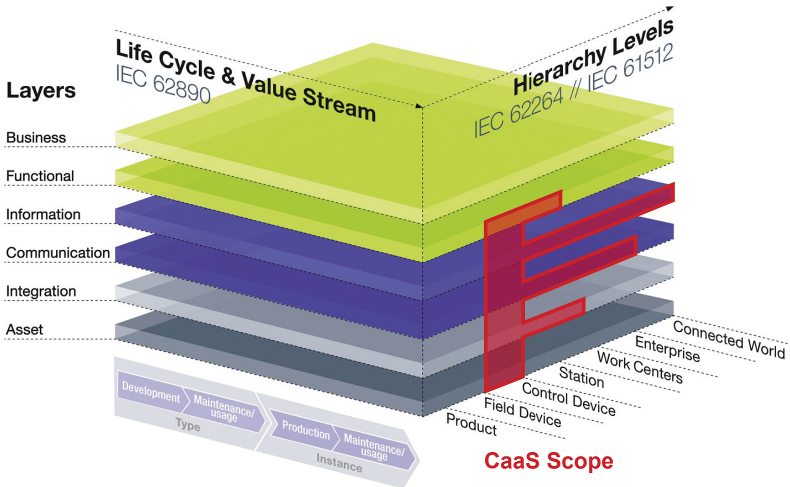


Figure J.1: Draft of a projection of CaaS to the RAMI 4.0 framework. The classification is carried out along the hierarchy level axis as CaaS is assumed to be independent of a product's life cycle. The original figure is copyrighted by Platform Industrie 4.0 [Adol15].

K OPC UA Architecture Model

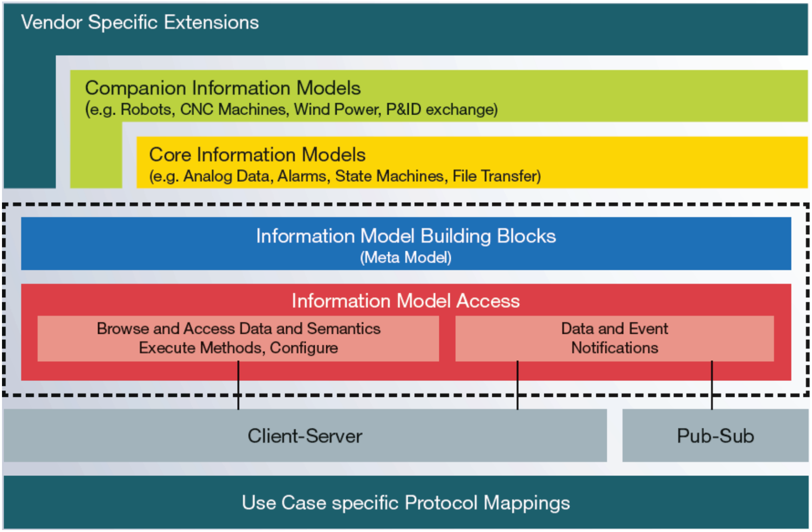


Figure K.1: OPC UA Architecture as outlined by the OPC Foundation [OPC 19].