2.3 Future Assembly with Distributed Sensor Services

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Kurzfassung

Verteilte Sensorinformationsdienste für die adaptiv automatisierte Montage

Mit *Line-less Mobile Assembly Systems* wird ein neuartiges Paradigma für die Montage großer, hochwertiger Produkte mit einem hohen Automatisierungs- und Rückverfolgungsgrad ab Losgröße 1 vorgestellt. Der kosteneffiziente und nachhaltige Einsatz kapazitätsbegrenzter Automationsressourcen sowie die kontinuierliche Verfügbarkeit und Analyse von In-Prozess-Daten für (teil-)automatisierte model- und wissensbasierte Entscheidungen tragen zu einer Erhöhung der Resilienz der Produktion bei.

Der Einsatz mobiler, standardisierter Automatisierungsressourcen in Verbindung mit einer uneingeschränkten und dynamischen Prozessplanung führt zur Auflösung fester Fabriklayouts mit Fixpunkt-basierter Automatisierung. Für dieses Szenario ist eine modellbasierte Systemsteuerung unerlässlich, welche wiederum detaillierte Modelle aufbauend auf rückführbaren Echtzeitinformationen erfordert. Die Informationsbereitstellung erfolgt durch *verteilte Sensordienste*, welche den erforderlichen allgegenwärtig verfügbaren messtechnischen Bezugsrahmen und die Infrastruktur bereitstellen. Eine serviceorientierte Architektur und entsprechende Sensormodelle ermöglichen die physikalische Verteilung heterogener Sensoren, verschiedene Schnittstellen und die flexible Nutzung von Rechenleistung auf unterschiedlicher Hardware.

Mit dem Mobilfunkstandard 5G steht seit kurzem eine Schlüsseltechnologie für datenintensive Industrieumgebungen mit mobilen Ressourcen zur Verfügung und motiviert so neuartige Montagesysteme für, u.a. die Automobil- und Luftfahrtindustrie.

Abstract

Future Assembly with Distributed Sensor Services

Line-less Mobile Assembly Systems are a novel paradigm addressing the production of large, high-value components with a high degree of automation and traceability at lot sizes as small as 1. This ambition is supported by a more cost-efficient and sustainable use of capacity-limited assembly resources as well as an increasing awareness for in-process data availability, analysis and continuity enabling (semi-)automated model- and knowledge-driven decisions, eventually contributing to more resilient production systems.

Deploying mobile, standardized automation resources in conjunction with unrestricted and dynamic process planning resolves fixed shop floor layouts with monument based automation. For this scenario, model-based system control is mandatory for reliable and resilient processes, which in turns demands elaborated models evaluable with traceable real-time information. *Distributed Sensor Services* complement this demand constituting a ubiquitously available metrology-based reference frame and infrastructure. The service-oriented architecture and sensor models allow for physical distribution and heterogeneity of sensors, diverse network and persistence interfaces and flexible utilization of computational capabilities on different hardware.

With 5G a key enabling technology for data-intensive industrial environments with numerous mobile resources has recently become available, motivating the presented concept and prototype of future assembly systems for, among others, automotive and aerospace use-cases.

1 Introduction and Motivation

Mass customization and personalized production are the mantra of today's manufacturing placing high demands on flexibility for producing companies [1, 2]. Megatrends such as digitalization, environmental consciousness, and increased regional individualization result in enhanced customer requirements, shorter product life-cycles, smaller batch sizes, and increased market uncertainty. Cost pressure continually increases due to emerging competitors from low-wage countries. Accordingly, manufacturing in high-wage countries is driven by a desire to increase automation and its resiliency even in low volume scenarios and for complex products.

Within the manufacturing domain, assembly is the business unit that is the most affected by the challenges mentioned above [3, 4]. Depending on the product type, assembly accounts for up to 50% of production time and 20% of production cost. In the automotive industry, up to 20 to 70% of direct labor cost is spent on assembly [5]. Complexity in industrial assembly is caused by product design, e.g. the total number of product variants, number of individual parts, functional dependencies, product size, and tolerances, as well as the plethora of possible assembly operations with an equally large amount of suitable equipment and tools. Contrary to machining, the sequence of operations in assembly is often less predetermined by product design, allowing the rearrangement of the assembly sequence to optimize the production line regarding throughput or utilization. This potential becomes especially apparent for large, complex products whose assembly operations are primarily manual.

Fixed material flows through spatially fixed assembly stations characterize most assembly systems to date. Product transfer systems are designed in such a way that the sequence of operations cannot be altered without substantial reconfiguration effort, resulting in rigid links regarding both spatial and temporal aspects [6]. Assembly stations, especially in the case of automation, are equipped for only few or even single processes and lack universality. Their setup and configuration for each process, as well as product configuration, takes significant time and effort. It limits the overall flexibility, as automated assembly equipment cannot be used to execute other processes for line balancing.

As an example, the assembly of primary major aerospace components such as wing or fuselage structures is done through riveting using purpose-built automation solutions that require extensive setup and high investments. Most other assembly processes, both outside and inside the structures, are done manually by highly trained operators. Automation challenges not only result from small lot sizes but often from factors including complex setup, adaptiveness, and utilization of single-purpose resources. Consequently, current automation and assembly system design is limiting for product design due to high reconfiguration efforts. Additional complexity arises from instabilities in manufacturing processes for small lot sizes. These result in physical deviations due to manufacturing tolerances, requiring on the fly adjustments of assembly processes. While tolerance narrowing is a widely deployed mitigation strategy, it is also a substantial cost driver. From an operations point of view, instabilities cause further complexity, as process times may differ significantly, making production line balancing a challenge. Adaptive process chains capable of taking these deviations into account would allow for a significant cost reduction. Furthermore, high-value complex products in assembly and also in maintenance, repair, and overhaul (MRO) require first-time-right approaches due to safety considerations and thereby traceability and documentation requirements.

Figure 1: Left: Manual disassembly of a jet engine for overhaul, © Lufthansa Technik AG, Right: Typical assembly line in aerospace, © The Boeing Company

Figure 1 shows a step of the complex, manual disassembly of a jet engine for overhaul, which involves functional testing of all critical components with a work scope changing individually per engine depending on the respective state. In total, these considerations illustrate the potential benefit of an increased automation level beyond the scope of immediate cost reduction.

Adaptiveness from an automation point of view requires the ability to detect the current process state and to determine the next operations and their parameters autonomously. From an organizational point of view, increased flexibility for resource assignment and spatial as well as temporal restrictions is required. Hence, conventional approaches to assembly organization and automation based on single-purpose machines, fixed station resources, and locations, and predetermined assembly sequences are not affordable.

This contribution introduces *Line-less Mobile Assembly Systems* (LMAS) as a novel paradigm for the industrial assembly of large, high-value components down to lot size 1 and its technological foundations. Its technical materialization is considered to be enabled by the emergence of key enabling technologies in the fields of metrology, mobile robotics, scalable computing and wireless communication technologies. LMAS aim at enabling automation in complex assembly systems, as found in automotive and aerospace final assembly lines or MRO, with economic viability compared to state-of-the-art approaches with high participation of human operators.

While automation has been a substantial part of previous industrial revolutions (cf. Computer Integrated Manufacturing - CIM), in aforementioned systems it faces the challenge of lacking repeatability. Volatility in products, processes and assembly systems require to extend the scope of automation to autonomous identification and adaption of the traditionally automated applications, endorsing the vision of *Automation of Automation.* Inevitably, the adhering control loops require an elevated amount of information and appropriate models of relevant system entities to maintain stable operation within the envisaged volatility which is even increased by the LMAS approach. Therewith LMAS can be classified as an implementation of cyber-physical production systems, implying that the ubiquitous availability of sensor information is mandatory to synchronize real systems and virtual models. Technically, interoperability, available communication means, system architecture, data integrity, available computing capabilities and implementation feasibility must be considered. Physically, the measurement data acquired by heterogeneous systems in their respective local context must be aggregated in a global scope and made interpretable by the virtual models.

These requirements accumulate in the presented concept of *Distributed Sensor Services*, which constitute a virtual reference frame taking over process stabilizing characteristics from predetermined physical synchronization. Referring to LMAS, this prospect is illustrated in Large-Scale coordinate measuring instruments and distributed environment sensors replacing fixed spatial monuments and environmental stabilization.

2 Line-less Mobile Assembly Systems

Line-less Mobile Assembly Systems are the next step in the continuous evolution of production systems from dedicated manufacturing lines to line-less assembly systems. This chapter provides an overview on production system paradigms, reviews industrial requirements, and provides an in-depth explanation of LMAS.

2.1 Evolution of Changeable Production Systems in Industrial Assembly

Today’s production system design focuses on the concepts of changeability, flexibility, and reconfigurability. *Changeability* is defined as “characteristics to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels to change impulses economically” [7]. It is enabled through changeability capabilities, which comprise means i.a. universality, scalability, modularity, mobility, and compatibility [8, 9]. *Flexibility* refers to a manufacturing system’s ability to change its capabilities without changing its configuration. *Reconfigurability* refers to a manufacturing system’s ability to change its behavior by changing its configuration. Since the 19th century and with increasing digitalization, production system design has evolved from dedicated manufacturing lines (DML).

Flexible Manufacturing Systems (FMS), introduced in the 1980s, allow the manufacturing of a variety of part types. They offer built-in flexibility, permitting process adaptations, and, partially, production volume adjustment within pre-defined boundaries without physical changes to the system [10, 11]. FMS link several flexible CNC machining centers through an automated transport system for product or pallet transport between operations. The machine selection is based on requirements from a large product portfolio, to include as many parts as possible. A central automated managing system controls material and tool flow [4, 12]. Typical FMS configurations provide different routes for each product, by utilizing a central transport system that allows transport between two arbitrary locations (c.f. Figure 2, left). FMS have very high product flexibility, but, due to their universal nature, lack efficiency.

Reconfigurable Manufacturing Systems (RMS) combine the high throughput of DML (use of dedicated machines) and the flexibility of FMS (use of routing flexibility). RMS configurations are designed with ease of change in structure, hardware, and software in mind to adjust production capacity and functionality. They are designed for product families to allow for more specialized equipment. Similar to FMS, RMS include several redundant single-purpose and flexible manufacturing machines, transport systems, robots, fixtures, tools, buffers, and control systems [13–15]. Reconfiguration results from adding, removing, or modifying single components or entire branches and can be made repeatedly and cost-effectively during operation. The configuration, i.e. the degree of cross-link between machines, determines the degree of adaptiveness of an RMS. In practice, RMS are often separated into cells with multiple, identical machines that are connected by a backbone using gantry style transport systems (c.f. Figure 2, center). Compared to FMS, efficiency and scalability of RMS are higher, while product flexibility is reduced.

Recently, the concept of Line-less Assembly Systems (LAS), based on the adaptation of RMS principles to assembly systems, has gained popularity. Its governing principle is to resolve spatial and temporal constraints in material flow to achieve maximum routing flexibility. Within LAS, individual work stations become independent from a central cycle time. Workstations have fixed locations and are connected by transport systems in such a way that an arbitrary sequence of stations is possible [16–18]. Workstations have a fixed work scope, which is partially redundant to other workstations to improve workload balancing (c.f. Figure 2, right). Sequencing, workstation allocation, and, subsequently, routing for each assembly process is done within a central control system. The ability to exploit variability in the sequence of operations (precedence graph) has been proven to be beneficial regarding utilization and lead time [19, 20]. LAS are favorable in production scenarios with a high degree of cycle time spread. Transportation efforts limit their applicability to large-scale products, as spatial requirements for transport efforts become high.

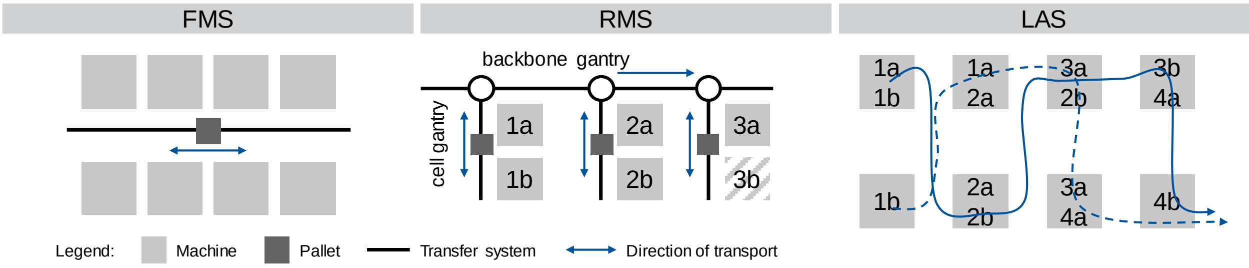


Figure 2: Overview on typical configurations for Flexible Manufacturing Systems (FMS), Reconfigurable Manufacturing Systems (RMS), and Line-less Assembly Systems (LAS)

2.2 Considered Industrial Requirements

Applying the paradigm of line-less assembly to the production of large-scale products requires the consideration of further requirements. In addition to general flexibility requirements, as fulfilled by LAS, the expert group has identified the following criteria, specific to the production of high-value, large-scale and small-batch assembly:

- Structural flexibility: Ease (time and cost) of rearranging and setting up new work stations for different tasks without interfering with operations,
- Resource flexibility: Large number of possible configurations of resources by utilizing standardized interfaces and modules to achieve multi-purpose-machines,
- Degree of automation: Ability to incorporate both manual and automated processes in hybrid environments and facilitate temporary changeover,
- Incorporation of large-scale products: Organizational design considering the specific needs of large scale products (e.g. size, long processing times, long cycle times, complexity),
- Mobilization of resources: Incorporation of mobile resources (e.g. mobile manipulators, mobile robots),
- Routing flexibility: Allows for multiple job routes per product type using existing resources in a different order without restrictions of the production sequence,
- Process decoupling: Temporal and spatial independence of resources and processes providing the ability to cope with process time fluctuations,
- Inherently flexible automation: Automation must not inhibit product innovations,
- Quality improvement: The use of automation must facilitate first-time-right approaches in dealing with tolerance affected parts.

2.3 Core Principles of Line-less Mobile Assembly Systems

Line-less mobile Assembly Systems (LMAS) combine the concept of temporal and spatial decoupling of resources with modern approaches regarding the mobilization of all resources that are relevant during industrial assembly. Mobilization allows to bring resources and product together at freely chosen positions in the factory and thus makes use of the paradigm of moving resources to the product, which can be beneficial for large-scale products (c.f. Figure 3). The use of standardized interfaces and machinery allows the creation of multi-purpose resources. These can be changed over to other operations and quickly increase utilization, as the flexibility of resource assignment to jobs is increased. Within LMAS production planning has to perform resource assignment, operations sequencing, and location planning within the factory. LMAS are defined as follows:

LMAS are assembly systems which allow continuous adaptation and optimization of production through individual job routes based on the completely free allocation of orders, resources, time, and place of work within the factory.

A fundamental concept within LMAS is the concept of a job route, tying together assignment, scheduling, and location decisions. A job route within LMAS is defined as:

A job route describes a tuple of resource allocation, process sequence, time sequence, and spatial allocation of all production steps necessary for the assembly of a specific product.

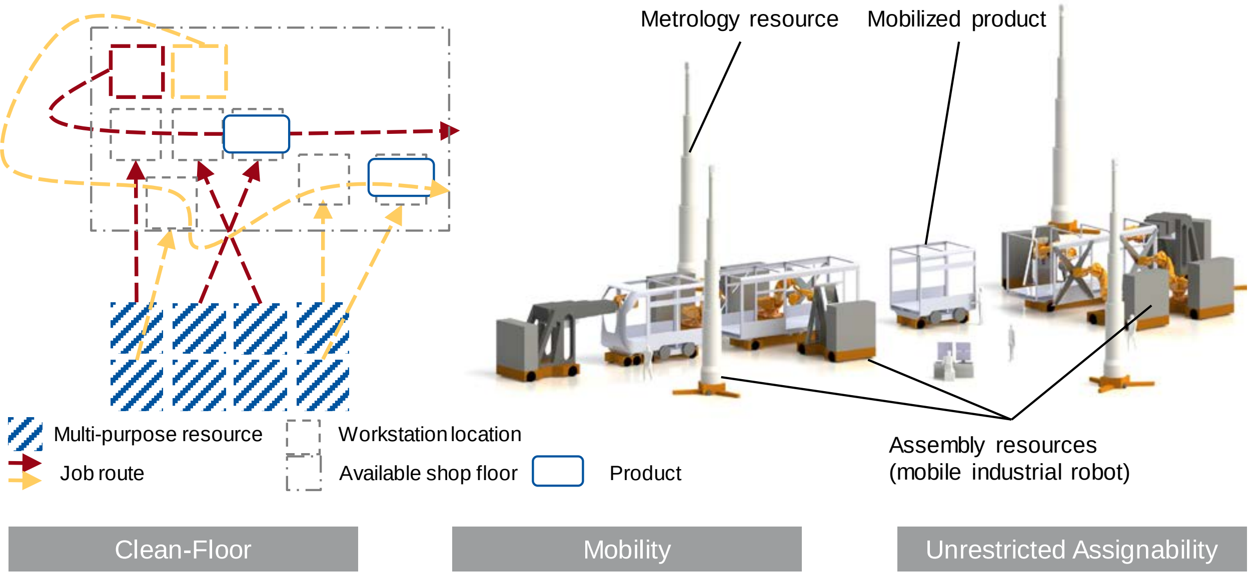


Figure 3: Line-less Mobile Assembly System (LMAS) Principle

LMAS are designed to be primarily automated systems being able to react to changes in the production program autonomously. Especially in the assembly of large scale products, manual operations play a significant role due to accessibility, low volume, and handling of flexible parts. The design and operation of LMAS take place on multiple levels from the control of individual resources (e.g. path planning for a robot during assembly) to the overall routing and scheduling of jobs within the factory. Accordingly, different planning horizons are of interest. Reconfiguration in LMAS happens both on a medium time scale (e.g. per shift) as well as on a short term time scale (i.e. reacting to disturbances) to optimize the utilization of resources on a micro-level.

Similar to LAS, LMAS do not have a fixed cycle time but rather decoupled processing times for each job based on the availability of resources in the current configuration of the assembly system. The allocation of resources to tasks during operation is an operation research problem during production planning and scheduling [21]. Decisions on the number and type of available resources, boundary conditions, and optimization criteria are made during the assembly system design phase.

LMAS are implemented based on three fundamental principles [22]:

- (1) Clean floor approach,
- (2) Mobilization of all assembly relevant resources within the factory,
- (3) Unrestricted assignability of resources and products to locations and resources to jobs.

The term *clean floor approach* refers to the design of the factory building to provide a large coherent shop floor space with as few physical obstacles (e.g. support columns, fixed machinery, other infrastructure) as possible. Any fixed structure impedes reconfiguration and resource movements due to spatial constraints. The shop floor is considered a large staging area where production processes may be executed at any time and in any place. Location planning needs to determine where which actions take place while maintaining operational stability explicitly avoiding deadlocks, which may occur if mobile resources are arranged in such a way that they become boxed in and cannot move independently from each other. Accordingly, space needs to be allocated for assembly operations, material flow (intralogistics), and movement of products and assembly resources. The allocation of workstations within the factory is thus moved from traditional factory layout planning on workstation level to a part of operations planning.

The *mobilization* of all relevant resources on the shop floor is fundamental to make use of the clean floor approach. It comprises the potential movement of all resources related to assembly, thus dissolving the concept of fixed stationary work stations (monuments). Resources include all production resources, such as single or multi-purpose assembly machines, metrology systems, tool exchange systems, and fixtures. All product-related entities - the main product and its parts - are subject to mobilization as well. They are considered to be mobile; movement is done through appropriate resources. Mobilization may result from discrete floor-bound systems such as mobile robots, as well as non-floor bound mobile transport robots (e.g. Unmanned Aerial Vehicles (UAV)). Resources can move either actively by being a part of a mobile robot or passively by being designed in such a way, that they may be picked up by a mobile robot (e.g. a platform with a mobile robot, fixture, product).

The third principle adds resource flexibility (and further forms of flexibility) by requiring *unrestricted assignability of resources* to jobs and of resources to locations within the usable shop floor. Following the underlying principle of redundancy in LAS, the third principle requires the deployment of redundant universal resources. This can be achieved through a suitable modularization strategy to exchange tools and fixtures among robots and by utilizing mobile robots to transport different entities (e.g. products, robots, fixtures, materials, parts). Redundant resources provide production planning with more options for resource assignment and, thus, more balancing capabilities. Ultimately, this results in an assembly system that can be reconfigured to the highest possible extent by changing not only which individual resources perform which task, but also the location where process execution is being fulfilled. LMAS thus combine real-time determined job routes with the spatial aspect of factory layout planning. To facilitate the design and operation of LMAS, two levels of modeling – factory configuration and station configuration – are used.

LMAS are highly complex systems, consisting of a large number of processes, resources, products, and parts. To facilitate their design and to reduce planning complexity, three distinct hierarchical levels are defined as depicted in Figure 3. The levels are vehicles to enhance the ease of designing LMAS, improve human comprehensibility, and make operations planning less complex. The most granular level is the process configuration level, governing assembly processes, parameters, and sequence. While LMAS do not have stations and line layouts in the conventional physical sense, it uses the concept of virtual, temporary stations represented on the station configuration level. The factory configuration level represents the entire space that is available for LMAS operation [21, 22].

3 Emerging Key Enabling Technologies for Future Assembly

Mastering the complexity of LMAS operation is facilitated through recent advances in several key enabling technologies (c.f. Figure 4). Central to the management of LMAS is the ability to design, process, and interpret complex systems models for all hierarchical levels. Modern highly scalable cloud and edge computing platforms allow the execution of these models. Specific to the vision of Automation of Automation are advances in mobile robotics, sensors and communication technologies, which are summarized below.

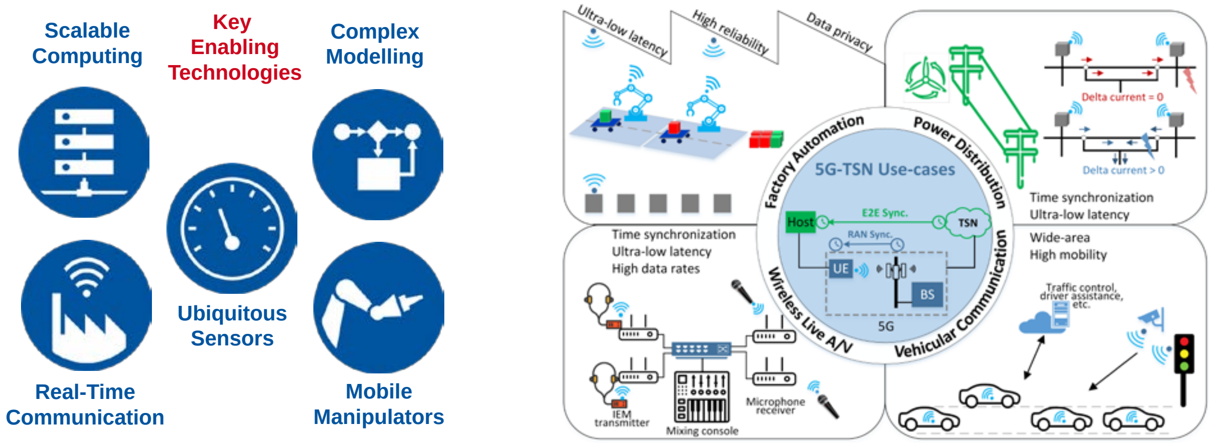
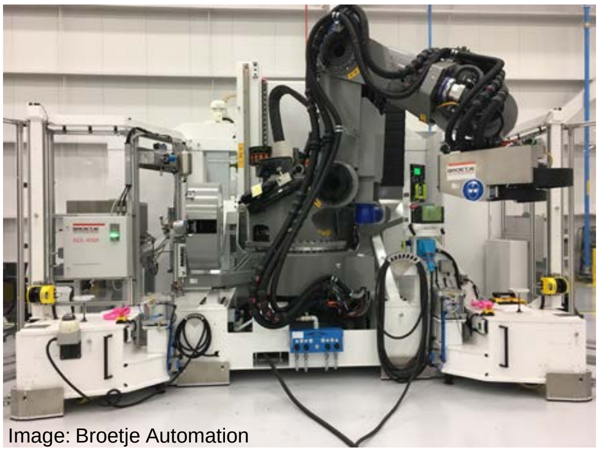


Figure 4: Left: Key Enabling Technologies overview, Right: 5G Application Domains with timing requirements, © Ericsson

3.1 Mobile Manipulators

Mobilization is an enabler for changeable production systems, especially for automation, as the reconfiguration of conventional automation solutions is limited. The term “mobile robot” refers to general robotic systems that are not fixed to one physical location and have the capability to move around in their environment. In their purest form, they consist of chassis, drives, sensors, and control systems. Contrary to Automated Guided Vehicles (AGV), mobile robots are generally designed for autonomous driving without requiring locally fixed guidance systems. In the industrial context, the most common applications are found in intralogistics tasks. Numerous automation suppliers provide standardized as well as customized solutions.

Mobile manipulators expand mobile robots by adding a robotic manipulator arm, e.g. a conventional or collaborative industrial 6-DoF robot. They consist of a mobile robot base, local storage space (e.g. for work piece carriers, tools), manipulator arms, energy supply, grippers, control systems, and safety systems. Additional sensors and vision systems help to recognize objects and obstacles during manipulation.



Potentials

- Enables temporary automation and sharing of automation resources between workplaces
- Modular design of endeffector tooling provides high process flexibility
- Mobility increases reconfigurability of automation
- Increased work envelope allows cost-effective operations on large products

Challenges

- Safe human-robot-interaction requires additional measures and regulations
- High system complexity may result in initially unstable operation
- Safe, reliable and wireless communication is required to integrate mobile manipulators into the factory

Figure 5: Left: Mobile manipulators for machine tending, © Fanuc; Right: Large-scale mobile manipulator for robotic drilling and riveting, © Broetje-Automation GmbH

Mobile manipulators often use omnidirectional instead of differential drives to increase the maneuverability of the platform. They combine the advantages of both industrial robots and mobile robots (c.f. Figure 5). Industrial applications for mobile manipulators can be found in machine tending (parts, tools, fixtures), commissioning, and assembly (e.g. riveting, glue applications, tightening), as well as co-working when collaborative robots are used. Applications in health care and general service robotics are further research subjects. While several prototypes and early industrial products are available, mobile manipulators have not achieved widespread industrial use yet. Figure 5 shows mobile manipulators for machine tending using a collaborative robot as well as a custom-designed large-scale 6-DoF system for robot-based drilling and riveting.

3.2 Ubiquitous Metrology and Sensors

The increased demand for functional testing for products of high value and relevant to security, a wide range of industrial metrology equipment has emerged, and, as perceived by the authors, nearly every system is somehow used. With the trend to shorter quality control cycles, many instruments have been optimized to be deployed directly on the shop floor rather than in a separate measurement room, making them applicable candidates for automation-integrated metrology. The variety of available instruments is illustrated for the domain of Large-Scale Coordinate Metrology manifesting a necessary trade-off between uncertainty and working volume, among other parameters, including cost [23, 24].

Moreover, an increasing amount of low-cost sensors is brought to market due to their application in consumer electronics, e.g. inertial measurement units (IMU) used in smartphones or environment sensors for home automation. In addition, massive sensor deployment is enabled for systems where a large number of distributed, coarse measurements is more favorable than highly accurate but sparse information. In synopsis, the ubiquitous availability of industrial metrology systems and basic sensors building the hardware is the basis for Distributed Sensor Services (DSS), as introduced in chapter 4.

3.3 Communication Technologies and Computing Platforms

5G is a new, open wireless mobile communication standard that is globally deployed and hence has a global ecosystem. It is operating in a licensed spectrum, which allows the design for guaranteed performance. In addition to the expected consumer market, 5G also focusses on proving connectivity for the Industrial Internet of Things (IIoT) in various fields depicted in Figure 4. Alignment of 5G standardization and design with industrial needs is provided e.g. via the 5G-ACIA alliance. By design, 5G is targeted at a broad mix of services, ranging from high throughput image streams over infrequent sensor reports to deterministic low latency control, which is achieved by built-in QoS mechanisms and performance management. The possibility for non-public networks (in contrast to traditional public mobile network services) moreover allows the deployment of local network solutions that are designed for a specific industry needs and provides deterministic performance, resilience, security, and data retention, making it a candidate for ultra-reliable industrial communication with millisecond-level latency [25]. At the same time, 5G provides novel capabilities of LAN communication and, therefore, can integrate with an existing LAN infrastructure, including the latest IEEE 802.1 time-sensitive networking with microsecond clock synchronization. All these novel capabilities make 5G outstanding as a wireless communication technology and a key enabler for scenario-specific communication design in automation systems as covered in chapter 5.

Recent developments in consumer-oriented electronics and web services have led to the emergence of highly scalable, resilient, and performant computing platforms and a paradigm shift towards servitization and containerization to achieve demand-tailored and cost-efficient availability. As an illustrative example, the amount of participating entities, processed data, and subsystems in social networks is outperforming any industrial domain at the time of writing, such that the adaption of established technologies from the domain of consumer web services becomes an area of research. Besides, smart consumer devices, i.e. phones, tablets, and wearables, have enriched the possible ways of human-machine interaction, enabling distributed and intuitive user interface.

4 Distributed Sensor Services and Functional Value Models

Metrology is a key element of cyber-physical production, constituting the digitizing interface between physical and virtual systems. For future assembly paradigms with a clean shop floor approach and the implied absence of monuments, the typically required global reference frame can be virtually instantiated as metrological reference frame [26]. With the additional degree of volatility introduced by the mobility of all entities, spatial reference and real-time model evaluation are critical to maintain stable processes against the background of elevated tolerance and functional requirements [23]. In the context of modelling, real-time is interpreted as the requirement of a virtual, operable model being synchronized sufficiently fast to achieve the necessary modelling accuracy. The functional requirements are motivating today’s state-of-the-art in shop floor integrated metrology, e.g. laser trackers in aerospace assembly, near-line coordinate measurement machines (CMM) and handheld inspection devices of various kinds in maintenance and repair operations. However, the scope of use of the acquired data is mostly limited to individual, local applications, even if the need for a holistic approach to sensor, sensor data and software management is acknowledged. Emerging integration efforts are currently often limited to basic centralized data collection with little feedback to users or autonomous agents, which in turns hinders the creation of value. A recurring reason is the disproportionate overhead for pure software interface engineering when implementing complex, scalable and resilient automation systems due to the lack of *interoperability*. The latter is defined in

ISO 2381-1 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”. EVERTZ ET AL. identify three main technical issues to achieve interoperability in the context of service-oriented architectures for process control [27]:

- The representation of data within the communication technology
- Delimitation, order, and type of individual items in a message
- The physical meaning and scale of the previously mentioned items

While the first issue relates to the communication technology used and is defined within the respective standardization effort, the second question is addressed by IoT protocols, for instance, OPC UA and MQTT. The last issue requires an appropriate, physically motivated model for the interface, which must consider a technology-agnostic, functional perspective as further discussed throughout this chapter.

4.1 Introduction to Distributed Sensor Services

Distributed Sensor Services is a term introduced by the authors subsuming the envisaged interoperable and ubiquitous availability of metrology instruments, respectively, general sensors in production environments. In explicit, the following properties are comprised within the individual subterms:

Sensor – Any entity leveraging physical principle to measure and subsequently digitize a real-world quantity is regarded as a sensor. Depending on the modeling perspective of the measurand, sensors can also be complex devices internally consisting of multiple sub-sensors and mathematical models, e.g. laser trackers.

Distributed – The sensors are physically distributed and measure in a local context. Their interfaces are decoupled as well as distributed across the network, and a third dimension of distribution is introduced by the distributed nature of modern computing and database platforms.

Services – Distribution and heterogeneity of sensors require increased awareness for interoperability. From the perspective of computer sciences, sensors are comparable to microservices encapsulating a concise functionality. Sensing (micro-)services can be deployed at different levels as proposed by SCHMITT ET AL. with the objective of decoupling a measurement, respectively, a subsequent decision from specific technological details [28].

The practical outcome of a shop floor provided with Distributed Sensor Services is the comprehensive ability of temporal, spatial, and general physical synchronization between real-word and virtual models and the resulting ubiquitous availability of information as the basis for decision-making. A key challenge to be resolved within the different levels of sensing servitization is the interpretative transition from a local to a global context as the latter is mandatory for a metrological reference frame. This challenge is also reflected in the architecture design of a suited infrastructure, as discussed in chapter 5.

4.2 Role of Industrial Communication Protocols

The main reason for the severe software development overhead in the design and implementation of complex automation systems is the diversity of communication means and standardized, respectively proprietary communication protocols that have emerged. Among others, these comprise:

- Fieldbus-like and industrial Ethernet systems, e.g. CAN, Ethernet/IP, Powerlink or EtherCAT, focusing on timing aspects
- Consortial protocols aiming at general-purpose industrial connectivity, most notably OPC UA and MTConnect
- Protocols established in internet-based, private consumer-oriented applications, e.g. social media, smart homes, and smartphone connectivity. These include, among others, HTTP(s)/REST, MQTT, gRPC, and websockets.
- Technologies aimed at wireless, energy-aware communication, e.g. Bluetooth LE and LoraWAN
- Interfaces to databases, e.g. ODBC and SQL
- Protocols and programming languages specific to robots and machine tools

Convergence to a universal communication solution can currently not be observed [27] and backward compatibility is a strong requirement in traditional automation, such that Distributed Sensor services, respectively complex automation systems must account for this heterogeneity by design. Protocol routers and service adaptors are a possible solution, effectively allowing multi-protocol interfacing of services [27, 29]. First examples of commercially available protocol adaptors are *XI-Gateway* by Proxia Software AG and *KepServerEX* by PTC Inc. The general approach requires a service design that separates between characteristics specific to the protocol and actions specific to the resource, as shown in Figure 6. Messaging, resource addressing, user authentication, and serialization are expected to be handled by the protocol, while the implementation of a resource, e.g. a sensor, must be able to react to a general set of actions, such as data access or function invocation. In this perspective, industrial communication protocols become a tool rather than an interoperability enabler on their own.

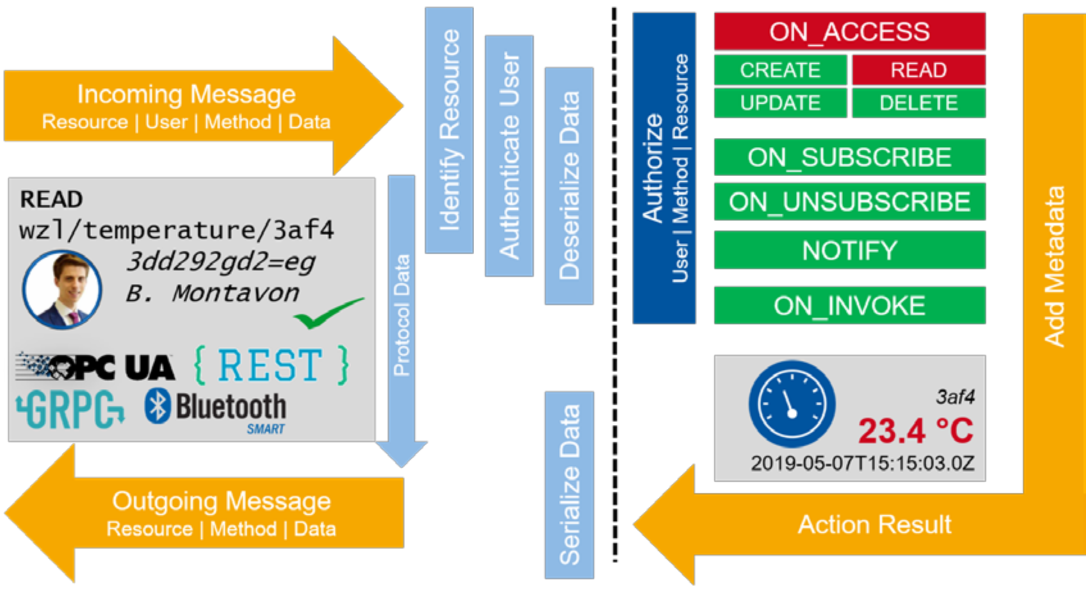


Figure 6: Separation between protocol-specific and resource-specific interaction

4.3 Functional Value Models enabling Technology-Agnostic Interoperability

Resolving the physical, respectively, contextual meaning of the data and functionality of a service is not only part of the previously mentioned technical interfacing challenges but also relevant from a perspective of technology and resource management. Preferably, the latter should take place on a technological and not product-specific abstraction level with the ultimate objective of interpreting the service approach as utilizing a resource to deliver the required data to the appropriate audience at the right time. This objective converges with the pragmatism characteristics of a model formulated by STACHOWIAK [30], endorsing a model-based approach to its solution.

At this point, a high degree of freedom for the concrete modeling approach prevails. With interoperability providing a focus on functional units over implementation details by definition, the authors propose a functional value modeling perspective: An interface should represent data, respectively, operations an entity can offer for applications in a technical system. Figure 7 illustrates this approach for different coordinate measuring systems: Although a laser tracker, an articulated arm, a classical Cartesian CMM and machine tool integrated probe are substantially different devices, they share the application of measuring 3D coordinates, e.g. for dimensional inspections, and subsequently offer the same core data record. Technological details such as individual encoder readings or kinematic compensations can instead be interpreted as internal matters which should be opaque to a broader audience. A mandatory part of the core data record is to have an appropriate set of metadata starting with label, timestamp, and unit for contextualization but, especially in the context of metrology, also extending to information on uncertainty and traceability, which are different among the technologies depicted in Figure 7. In general, the metadata set should describe relevant characteristics of the primary data resulting from the specific technological instantiation in an abstracted manner.

$$\underbrace{\boldsymbol{p} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} [\mathrm{m}]}_{\textbf{Position}} \quad \underbrace{\mathbf{V} = \begin{pmatrix} \sigma_{xx}^2 & \sigma_{xy}^2 & \sigma_{xz}^2 \\ \sigma_{yx}^2 & \sigma_{yy}^2 & \sigma_{yz}^2 \\ \sigma_{zx}^2 & \sigma_{zy}^2 & \sigma_{zz}^2 \end{pmatrix} [\mathrm{m}^2]}_{\textbf{Covariance}}$$

Metadata

- Timestamp
- Unique Identifier
- Label
- Confidence Level
- Statistical Distribution
- Traceability
- …

Figure 7: Unified modelling for coordinate measuring instruments

An additional requirement for the design of the models is their expressibility in the framework provided by the available communication protocols, e.g. in OPC UA’s data model or JSON serialization. In an ideal implementation, the identical digital representation is used for advertising the functional value from the moment an entity enters the network over its immediate processing until the ingestion into a data lake from which it can be retrieved for downstream analytic applications.

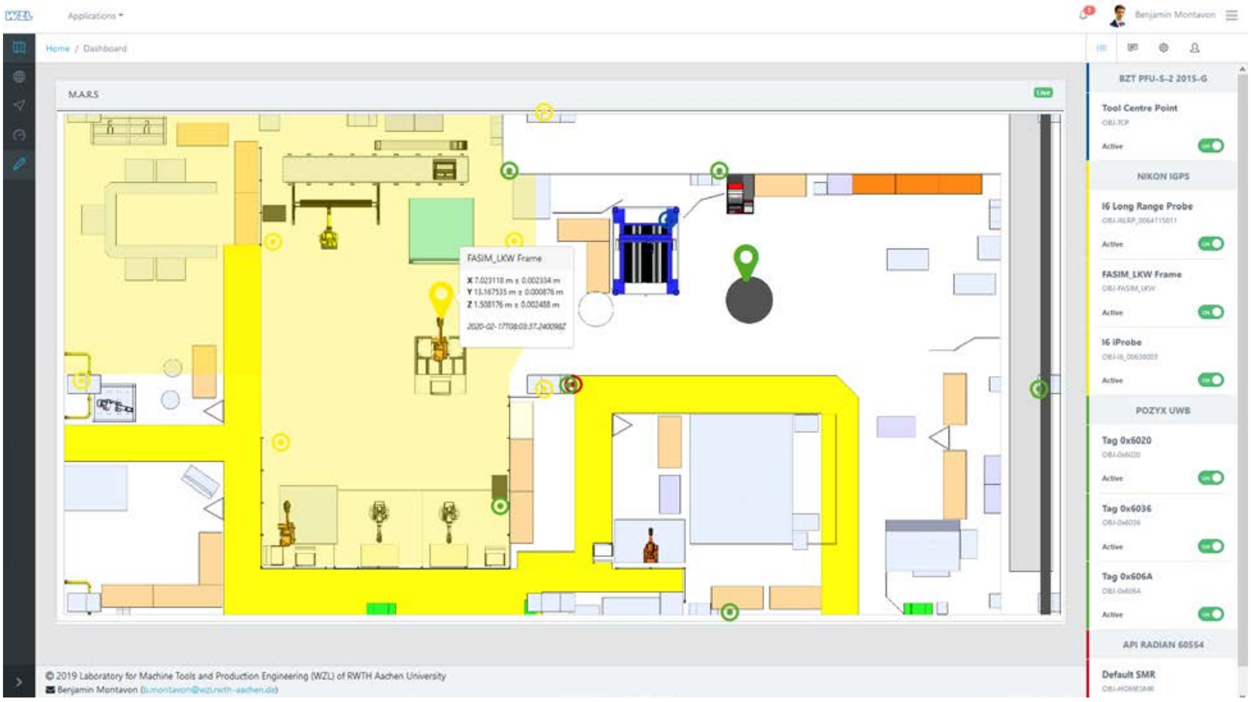


Figure 8: User interface of Coordinate Service Prototype

The model-based approach to interface design for Distributed Sensor Services has been evaluated by MONTAVON ET AL. [31, 32] in a Coordinate Service prototype combing different laser trackers, an indoor GPS, an ultra-wideband localization system and a calibrated machine tool to a virtual reference frame for the MARS laboratory at WZL (c.f. Figure 8). The data is ab initio communicated in JSON representation following a model similar to Figure 7 and used in the same format by, among others, processing ROS nodes, graphical user interfaces, and the ingestion into a time-series database. An additional data processing service provides the ability to transform the measurements from a local to a global coordinate system, including propagation of uncertainties [33], hence providing the necessary contextualization discussed in the upcoming chapter.

Similarly, a model to product requirements and automation resource capabilities for matching during LMAS operation was developed [34]. Matching refers to the process of finding capable resources for the execution of a job. Products are described using a work plan containing the possible sequences of requirements (c.f. Figure 9). Requirements relate to tasks that need to be performed to complete the assembly of the product, e.g. tightening of a cover. These are further specified using features, specifying further parameters such as the required tightening torque. Feature areas hold the concrete values of a feature, including the relevant unit, e.g. tightening torque 25Nm. The modeling of automation resources is more complex, as they contain not only concrete requirements but also all possible states considering capabilities, setup information, and current status. Each resource has a defined number of capabilities (e.g. screw tightening for DIN 912 socket head cap screws M4-M8, 1-50Nm), each described based on features, akin to the product model, cost items and setup states. Matching is done solely on feature base, while cost information is used in allocation optimization. Setup states include information on different resource setups, providing different capabilities.

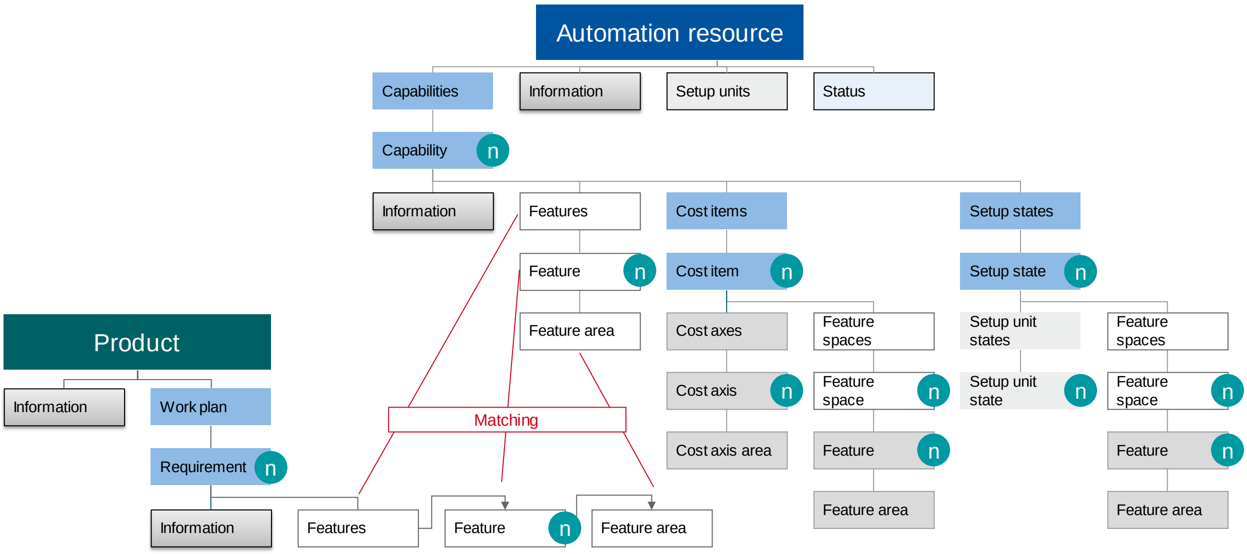


Figure 9: *Information model for matching product requirements with assembly resource capabilities (c.f. Grunert et al. [34])*

5 Semantic and Communication-Aware System Architecture

The architecture of future assembly, respectively autonomous automation systems sets the framework for their orchestration. Thereby the semantic structure and its dissection of subtasks into microservices determine the ability to separate workloads and implementations. On the other hand, available communication capabilities determine the flexibility in distributing these among different computing platforms respecting latency and bandwidth boundaries. A third boundary condition is introduced by the need for resilience, i.e. to enable scalability and avoid single points of failure.

The discussion on system architectures is omnipresent with interconnectedness declared as a strategic must among many companies. Moreover, a continuous growth in available (I)IoT platforms driven by major players in the internet domain such as Microsoft, Amazon, and Google fosters the trend to Infrastructure, Platform, and Software as a Service (IaaS, PaaS, SaaS). The latter enables highly scalable implementations at low capital cost with automatable deployment, being both an enabler and archetype for autonomous automation systems. However, this vision is confronted with privacy and network availability concerns in traditional automation requiring delicate assessment of external service providers. Eventually, the assumed inclusion of humans as part of future assembly system introduces the need for an appropriate safety infrastructure within the overall architecture.

Throughout this chapter an approach to a suitable architecture is taken without claiming exclusivity, as from a perspective of computer science, the existence of multiple valid designs for fulfilling the same task is assumed.

5.1 Five-Layer-Model for Resilient System Implementation

AL-FUQAHA ET AL. review different architectures in the context of IoT [35], of which the promoted five-layer architecture shown in Figure 10 can be leveraged as a rough blueprint for LMAS and Distributed Sensor Services. The objects layer comprises physical devices which in the present context correspond to the physical instances of automation resources, e.g. in the form of explicit of mobile robots and the physical sensors, respectively measurement instruments as devices themselves.

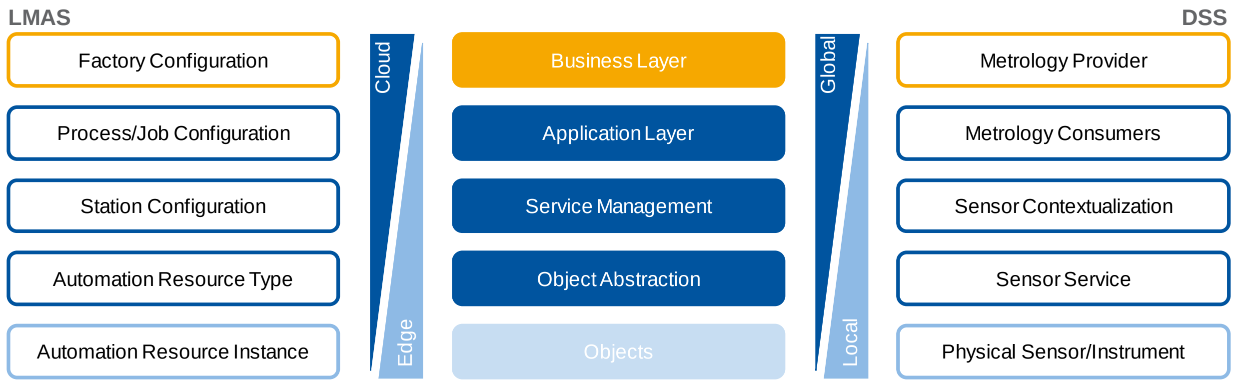


Figure 10: Architecture layers according to Al-Fuqaha et al. The top layer is a meta-layer and not regarded as technical layer.

The overlying *object abstraction layer* effectively connects the physical devices to the network and simultaneously provides the abstraction required for interoperability, corresponding to an interface based in a functional model, as discussed for Distributed Sensor Services. In LMAS, the first level of abstraction is established by the definition of automation resource types, e.g. robots characterized by specific capabilities. Subsequently, the *service management* encapsulates the necessary functions to leverage the abstracted objects in applications. In LMAS this layer translates to the configuration of a station, while for Distributed Sensor Services the primary task consists of the contextualization of the sensor data, e.g. the transformation from local to global coordinate system or annotation of measurements. The *application layer* as the fourth layer in IoT architecture poses the face to the customer. For an assembly system it is formed by the process, respectively a job that needs to be completed. From a perspective of sensor services, a consuming application can be arbitrary and even unknown to the service provider by definition [36]. Even if not explicitly suggested by Figure 10 an LMAS can be a metrology consumer, e.g. classifying the availability of a specific sensor service as a resource necessary for automation. At the top of the architecture, the *business layer is located*, which fulfills the task of managing the infrastructure and underlying service layers and can be seen as a kind of meta-layer. This task is reflected in the configuration and orchestration of the entire shop floor, respectively the factory, trying to achieve optimal operational efficiency and job fulfillment. This also applies to the coverage of the shop floor with sensor services and down to the illustrative question of whether a required quantity can be provided with sufficiently low measurement uncertainty. Without loss of generality the explicit separation of this task also allows its delegation, e.g. to a manufacturer continuously adapting and maintaining its provisioned equipment by means of software.

Among the layers both the modeling scope and intuitive hardware configuration migrate from a local to global scope at the same time, indicating the contrast between distributed and centralized processing respectively control, which in turn is interlaced with scalability and resilience of the system in terms of service availability. The elements in the objects layer naturally offer both through their physical independence and their abstraction in the subsequent layer, i.e. a failing robot as automation resource can be substituted by another available robot offering at least equivalent capabilities. The same holds for the instrument used as a resource in sensor services. As with the higher layers, the characteristic elements become dominated by software Load-balancing paradigms from traditional cloud computing can be adopted [37, 38]. This implies the use of dedicated, holistically managed computing platforms with built-in distribution and redundancy, in turn inferring network capabilities to connect individual system components to the former.

5.2 Incorporation of Communication Requirements

The performance of the available communication technologies is decisive when designing an actual hardware infrastructure for deploying the individual service layers of the architecture above. Vice versa, the statement of communication requirements within the design architecture is necessary to leverage adaptive communication technology, particularly in environments with 5G and hybrid network deployments. The authors therefore classify the operational characteristics of the service layers into four tiers as depicted in Figure 11. Most critical in terms of timing is the *shop floor tier,* which is expected to accommodate control loops related to the physical motion of fully mobilized, i.e. preferably wireless, entities. They are instantiated by combining objects from automation resources and sensor services in their abstraction layer in software, which is designated to run on edge devices. The embodiment of the latter depends on the reliable availability of a network link with ultra-low latency. It can be, for example, a dedicated platform located near the shop floor if 5G is identified as suitable wireless network technology or a miniaturized computing system carried on the mobile robot itself. Bandwidth is considered to be a mediocre issue due to the limited number of devices per area.

The aggregation of information with the transition from local to global scope manifests in the high bandwidth requirement of the *computing facility tier.* It is expected to match the capabilities found in traditional computing clusters, i.e. to evaluate complex algorithms intensive in computation and data use. Therewith it qualifies for the service management layer as the organization, respectively, the configuration of LMAS naturally is a problem of high complexity due to its degrees of freedom. Moreover, it is assumed that the tasks executed in this tier are not critically subjected to hard real-time. In the paradigm of Distributed Sensor Services, this tier is the place for long-term storage of sensor data and subsequently, also the platform of choice for data-driven analytic applications. The bandwidth requirement is reinforced due to the high network traffic to cluster formation in computing facilities. The network link between edge devices and computing facilities depends on the realization of the former and can be required to be wireless. The third tier is formed by the devices employed for *user interaction*, which pose significantly reduced requirements to the networking capability as they are determined by a usability experience. They are expected to be distributed in a wide area network, e.g. also in public cellular networks or at other companies in a scenario where system data exchange is part of the supply chain. Therewith the technical challenge rather lies in a strong access control mechanism providing sufficient security measures for the underlying tiers. A separate tier is dedicated to *safety*, i.e. any communication which is required in automated environments with human interaction. The dominating network link requirement here is guaranteed availability with defined latency, while only very little bandwidth is expected.

As indicated earlier the deduced demands to networking capabilities may be solved with hybrid technologies and do not solely rely on 5G as an enabler. However, it is expected that the latter will significantly facilitate the instantiation of automation-friendly wireless communication paths. The implementation of LMAS and Distributed Sensor Services within the proposed hardware tiers has been prototyped at the MARS laboratory at WZL: Sensors and actors communicate via Wi-Fi and Bluetooth Low Energy with heterogeneous edge devices in the form of work stations and Raspberry Pis ®. Gathered data is processed and stored on virtual machines residing in WZL's central PaaS infrastructure.

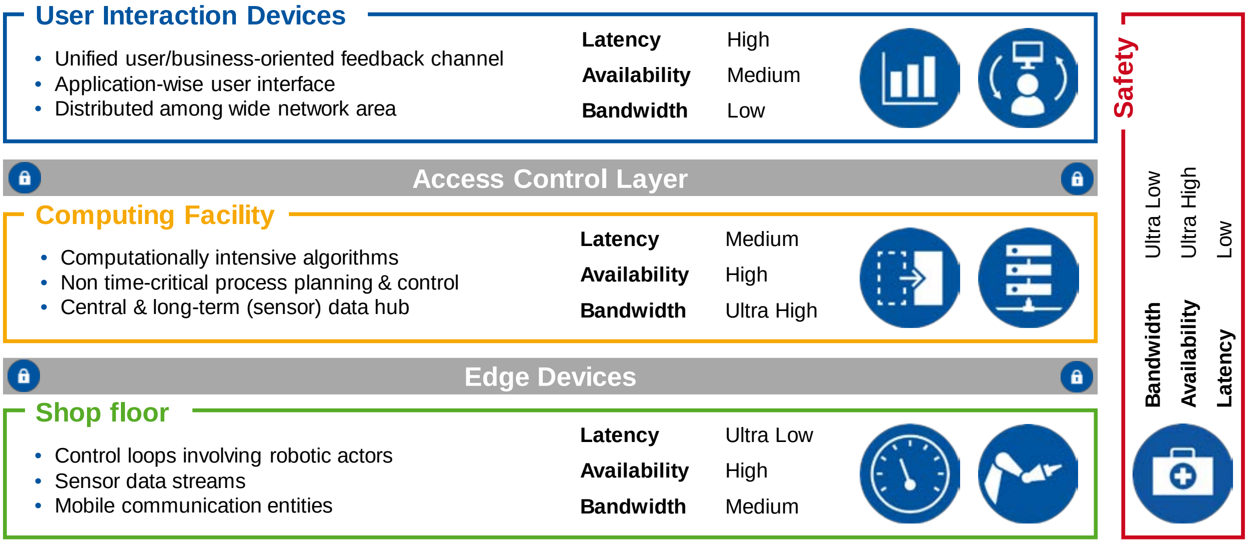


Figure 11: Communication requirements on different network levels

User interaction is realized in the form of responsive web applications accessible from the world-wide-web after a three-factor authentication. The coordinate service prototype shown in Figure 8 is entirely realized within the prototype architecture which has been proven advantageous in terms of maintenance, scalability, and long-term stability even in a scientific context. Experiencing wireless communication as the main bottleneck, the migration to a hybrid communication backbone, including 5G, as foreseen within the *5G Industry Campus Europe* project, will be pursued.

6 Industrial Applications and Economic Benefit

The LMAS concept and the enabling technologies above are motivated by the industrial need for increased adaptiveness to constantly changing requirements. The following reviews the generally expected prospects and provides already existing use cases for deployed technologies.

6.1 Use Case: Mobile Robotic Platforms in Aerospace Automation

Automation in aerospace assembly is predominantly used in the manufacture of primary structure elements such as fuselage and wing assembly. Traditional machine design for these applications relies on purpose-built, large machines with limited flexibility. These machines are designed for high productivity, cycle times of less than 10 s, and are limited with regard to flexibility. The relatively narrow scope of these machines creates an engineering challenge for integrators to design bespoke solutions for each client, resulting in additional engineering effort and thus cost. In recent years substantial efforts from both automation operators, i.e. OEMs and automation vendors and integrators, resulted in new automation solutions to improve flexibility while further increasing automation.

Flexible solutions for aerospace applications require a large number of degrees of freedom to accommodate widely varying product geometries and mobility so that the reach of machines can be adapted to the product size. Broetje-Automation has designed four mobile automation systems for structure assembly.

The PowerRACe system (Robot Assembly Cell) uses a custom made 6+1 axis robot, designed for stiffness and accuracy without requiring additional external measurement solutions and is aimed at mechanically demanding applications such as milling and riveting with high precision and speed (c.f. Figure 5, right). Mobility, redundant degrees of freedom in motion and exchangeable end effectors allow reconfiguration with little effort. The modularized platform concept allows highly flexible relocation. There are traditional systems available such as air cushions as well as integrated drives based on the company's AGV family, making the entire platform capable of autonomous movement.

In an industrial application realized for an aerospace customer, seven PowerRACe platforms have been deployed within a clean floor concept, so that they can be moved to work at various different workstations. This allows the automation of processes even within a framework of relatively low production rates that could not be economically automated using conventional, locally fixed systems.

To allow partial automation of tasks such as drilling, riveting, sanding and sealant application in difficult to reach areas and in conjunction with human operators, a lightweight, small-size system was developed on the same modular approach like the large PowerRACe system (c.f. Figure 12, left). As a basis for collaborative work, the platform uses a standard cobot system mounted on the Broetje-Automation AGV platform. The system is designed to autonomously navigate and reference itself against product geometry without any markers on the floor.

Further contribution towards the line-less approach is made by relocating logistic operation of the workpiece – in this case assembly of aircraft engines - onto the ceiling to reduce the total amount of floor-bound traffic (c.f. Figure 12, right). This allows not only a higher degree of flexibility for adapting the tooling equipment following the line less approach but also improves ergonomic for workers performing manual tasks.

Each of the systems have been successfully introduced into industrial applications. Especially for the robotic applications the key enabling technologies were in minimizing the kinematic inaccuracies within the systems. To achieve the necessary level of accuracy for aerospace production robot arms as well as the movable platform had to be design with a special focus to stiffness and robustness. The result enables the introduction into LMAS type production environments.

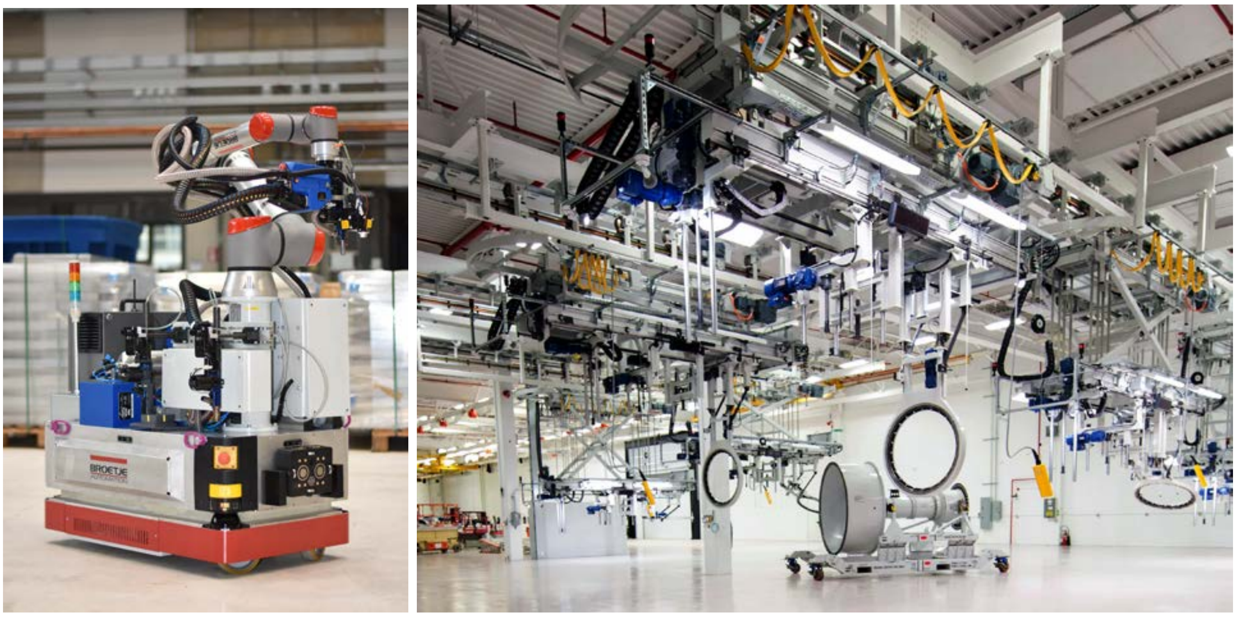


Figure 12: Left: Mobile collaborative robot for drilling, riveting and sealant application, Right: Ceiling based logistics solution for a clean floor assembly line, © Broetje-Automation GmbH

6.2 Use Case: Line-less Automotive Assembly

The automotive industry has seen a significant increase of variants, especially for middle-class to high-end models. For an Audi A3 there is a theoretical number of 10^{37} variants available, with a significant impact on assembly systems for both subassemblies, such as drive units, and the final product. Different product variants require different processes (e.g. convertibles require additional assembly steps for roof assembly over standard sedans) resulting in different assembly durations and sequences. To reduce the reconfiguration efforts of the approximately 160 assembly stations in final assembly lines and to increase and stabilize resource utilization, Audi designs its assembly systems accordingly.

Under the term “modular assembly”, following the idea of LAS, Audi uses an approach in which operations are assigned to individual independent work cells with defined work scopes. The processing time depends solely on the specific variant that is being assembled and is decoupled from the remaining system. Each cell is staffed by one or two operators that work with a constant rhythm. They are no longer required to adjust their speed to the conveyor speed and remain stationary, thus reducing the walking distance for each employee. The layout is designed in a way to enable individual product routing by means of AGVs (c.f. Figure 13, left). These are specifically designed to be able to navigate autonomously and use several fused sensor systems for localization and navigation. A complex centralized control system coordinates the production flow, including AGVs, machines, products, operators, and logistics. Dynamic routing algorithms take into account whether or not a resource is available and route the product to the next available resource. Internal studies of Audi have revealed increases in productivity by 20% while reducing space requirements by 10%.

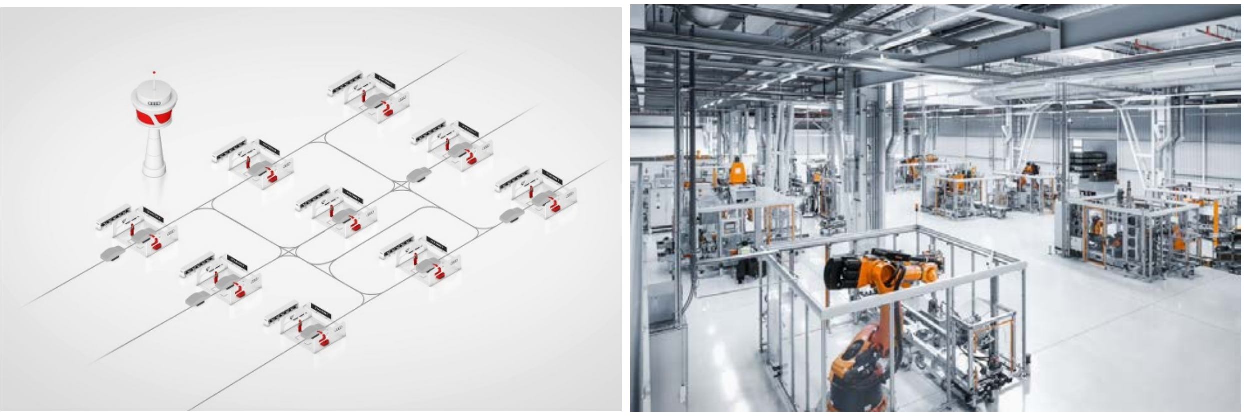


Figure 13: Principle layout for modular assembly system for automotive final assembly (left), flexible cells in electric motor production in Győr, Hungary (right), © Audi AG

In the automotive context, the LAS concept was initially developed for final assembly where AGVs are a key enabling technology. Within the “R8 Manufaktur” at Neckarsulm, Germany, Audi deployed AGVs for small-scale testing in a line-based scenario. In 2018 the LAS concept was transferred to a new assembly system for electric drive units in Győr, Hungary. The assembly process uses multiple assembly machines, robots, tightening stations, and measurement stations at fixed locations. A hybrid transfer strategy combines fixed transfer between stations using conveyor belts with AGV based transfer between decoupled assembly resources in areas, where the sequence of operations is different for each variant (c.f. Figure 13, right). Flexible routing is used to determine the ideal route for each product based on the availability of resources. While the assignment of products to resources is done dynamically, the order of operations for a product remains fixed. The flexible routing allows utilizing the same resource for recurring assembly processes, thus increasing utilization. The electric drive assembly system uses the LAS approach mostly towards the end of the assembly process, where the complexity of material logistics is reduced. An application of LAS to automotive final assembly requires further refinement of material supply concepts [39].

6.3 Use-Case: Metrology and Robotics

Kinematic inaccuracies are inherent to robotic platforms, regardless whether mobilized or not. They result from multiple sources, among them inaccurate kinematic models, insufficient stiffness, geometric error motions and thermal loads. Consequently, a compensation of kinematic inaccuracies by means of Large-Scale Metrology is of relevance for all robotic platforms used in applications with demanding requirements to the path accuracy. Two strategies for the latter objective can be distinguished: In the first case, a calibration measurement strategy within the robot's working volume can be pursued and used as input to a kinematic error model. While this offers the advantage of not requiring the permanent availability of a metrological reference, i.e. also circumventing line of sight issues, this method is susceptible to modeling deficiencies and accuracy degrading influences varying over time. The second, dynamic approach is to use a permanent metrological reference system capable of capturing all six degrees of freedom of a robotic end effector at a sufficiently high data rate and instantiate a direct control loop on the basis of this data, i.e. omitting kinematic model and encoder information of the robot's joints. Such a system has been realized within the European MegaROB project incorporating Hexagon's Leica AT960 laser tracker measuring relevant degrees of freedom at 1000 Hz delivered via an EtherCAT interface. Figure 14 shows the respective setup and the achieved improvement in path accuracy.

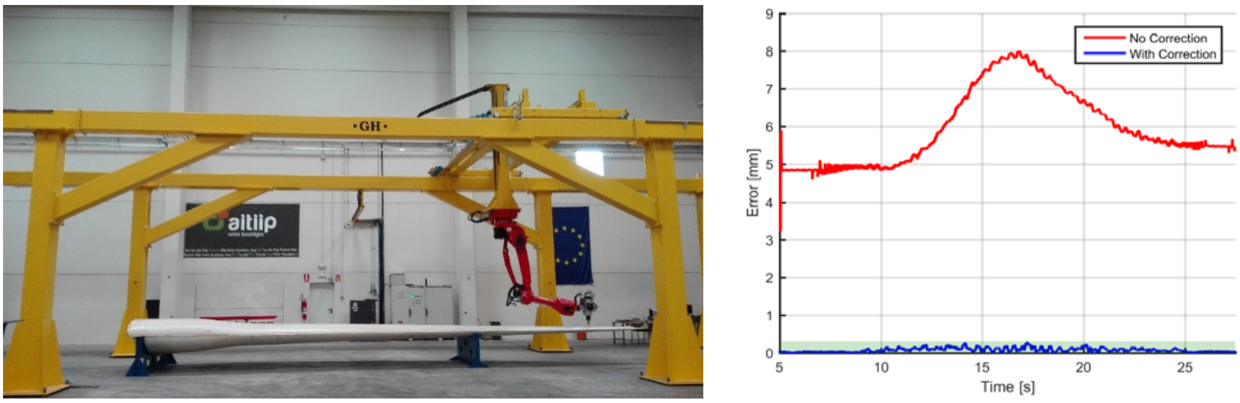


Figure 14: Large gantry and robot kinematic in a control loop based on Hexagon's Leica AT960 laser tracker with achieved improvement in path accuracy, © Hexagon.

In the case of traceable Large-Scale Metrology instruments being used as reference, the route to traceable geometry measurements directly on the shop floor using arbitrary kinematics opens. A practical example is Hexagon's Leica T-Scan, a device directly combining the required target for the Leica AT960 laser tracker with a laser line scanner. At the same time, this approach allows to register work pieces and kinematics in a common reference coordinate frame, constituting an enabling capability for stable process Lineless Mobile Assembly Systems. The LMAS vision also connects to mobilization of measurement systems, which from a pure metrology perspective is a strategy to overcome line of sight issues for large and complex work pieces, for instance manifesting in laser trackers and scanners moving around aerospace structures.

7 Conclusion and Outlook

Traditional automation approaches are reaching their limits for products and processes with high variance, large dimensions, small lot sizes, critical functional requirements, and inherent instabilities due to the lack of repeatability as an automation basis. The presented concept of *Line-less Mobile Assembly Systems* offers an approach to introduce, increase, or optimize automation in industrial areas facing the circumstances mentioned above. The envisaged prospects of high flexibility, the opportunity for hybrid automation, and profitable, respectively sustainable reuse of costly automation resources are reflected in the discussed examples from aerospace, automotive, and metrology. Moreover, the emerging degrees of freedom allow to autonomously react to unstable processes and the ability to adjust the factory to current needs on short time scales, thus increasing efficiency and resiliency. These considerations are also representative for the required change of mindset towards temporal and spatial decoupling of production systems through the mobilization of resources on a clean shop floor, even if a roll-out in brownfield situations may be exacerbated and high initial investments are required. Current and future advances in the field of mobile platforms and manipulators will be critical to an economically viable introduction of LMAS into existing and future assembly sites.

With 5G, a novel technology closing the gap for wireless, ultra-reliable, low-latency communication has become available, forming an enabler to implement control-loops for mobile manipulators without limiting the former to a local scope of information and computing. This is a prerequisite to the operation of LMAS relying on complex, virtual, and evaluable models which are synchronized to the real-world systems by the ubiquitous availability of sensor information. While many metrology systems are available today, the challenges arising from interoperability and heterogeneity are summarized under the term of Distributed Sensor Services, motivating the need for a model-based, service-oriented approach to metrology data communication. Consequently, a paradigm shift towards managing metrology on a capability and information contribution level rather than on a specific technological and protocol level is required.

The authors consider that all key enabling technologies and core concepts to implement LMAS are available today, such that the focus of future research, design, and engineering activities lies in the realization of exemplary systems with industrial maturity. In parallel, many subaspects of LMAS and DSS may already be beneficially implemented in industrial applications, e.g. adaptive automation for stationary processes with high variance, metrology-based accuracy improvement of large kinematics, line-less assembly organization or technology-agnostic, interoperable communication of metrology data. In addition to that, the potential benefits of developing LMAS and DSS apply to many industrial sectors.

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