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Conceptual control architecture for future highly flexible production systems

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Abstract

The trend towards more customized products with shorter product life cycles requires rethinking of current production systems. Due to the increasing demands for flexibility and adaptability, agile state of the art production systems come close to their limits. To improve adaptability to volatile markets, the fundamental concepts of production systems must be reviewed. With the novel production system Wertstromkinematik, the limits of flexibility and agility will be pushed further. By using several units of an identical universal robot kinematic with suitable end effectors, complete versatile value streams can be mapped. In this paper a conceptual control architecture for this novel production concept is presented and discussed in four different test environments. These examined environments comprise the core functions of the new production concept coupling of robot kinematics and machine self-optimization as well as two use cases involving the use of digital CAD-CAM-chains will be discussed in detail. Based on these topics possible restrictions and solutions regarding the overall communication architecture will be presented and discussed.

Keywords: Robot; Cognitive Robotics; Robot cooperation;

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1. Introduction

The challenges in a volatile, uncertain, complex and ambiguous market (VUCA) [1] require new methods and concepts in production science. In [2] an overview of how to address these future challenges with machine learning methods is given. However, the successful transformation of production systems in a VUCA environment cannot be achieved by software solutions exclusively. The hardware of the production concept also has to be rethought. More flexible and adaptable production machines are necessary. In [3] a clear explanation of full flexibility of production systems is defined by four aspects: route variation (Routing Flexibility), physical rearrangement of hardware (Structural Flexibility), the ability to integrate new processes into existing production resources (Resource Flexibility) and being able to expand production resources at any time (Expansion Flexibility).

The concept of Wertstromkinematik (WSK) [4] addresses all these aspects of flexibility in a new production system. The vision behind WSK is to create a production system entirely built with several units of an identical universal robot kinematic, which can perform all tasks necessary in a production (see Fig. 1). This includes not only handling tasks common in industrial robotics, but also manufacturing and assembly processes as well as quality assurance.

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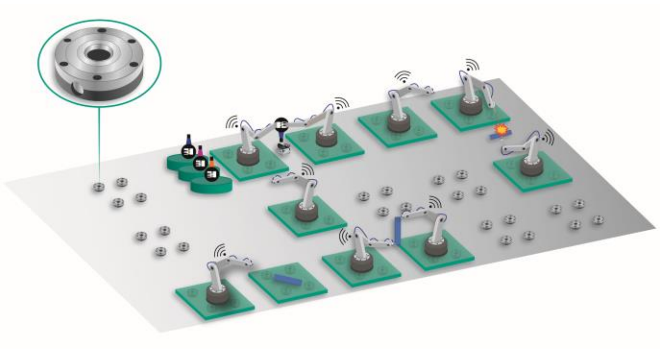

Fig. 1. Visualization of the WSK concept system [4]

With the elimination of expensive, less flexible special machines within a value stream the flexibility of the production system can be greatly increased and thus makes it much easier for operators to manufacture varying products on the same production line. However, the main obstacle in realizing a complete robot based manufacturing is their lack of stiffness compared to specialized machines. To solve this problem, several robot kinematics are coupled together in order to jointly execute a manufacturing process by utilizing the resulting increased overall stiffness.

Replacing specialized machines with flexible robot kinematics provide resource and routing flexibility, due to their inherent versatility and capability of executing completely different manufacturing processes with different tools. To cover structural and expansion flexibility the production floor in the WSK concept is covered with a grid of clamping pots. This allows the robot kinematics to be repositioned quickly and accurately when a rearrangement is necessary, e.g. in case of fluctuating demands. Furthermore planning and ramp up of production systems are supported by a digital process chain to speed up the reconfiguration of the production system.

The dynamic adaptation of such a production system to external factors creates new requirements for the control architecture. A more flexible and modular control architecture is required. Therefore chapter 2 presents a new control architecture target system. In chapter 3 the capability of the target system will be investigated in four different cases. Chapter 4 summarizes the results and gives a brief outlook.

2. Control architectures and approach for a target system

Conventional control architectures are built as a strictly hierarchical structure, which is generally referred to as the automation pyramid (see Fig. 2a). The communication links of one level are restricted to neighboring levels. In addition, each control unit in the architecture is assigned to a specific purpose. This rigid structure does not satisfy the requirements of a versatile production system. In such a production system, the control components must be as flexible as the hardware. This means that a modular architecture is required which allows any communication paths between the levels. Specific software solutions, for example real-time models or data processing for production optimization, will also play a greater role in the future, especially in robot-based production concepts. Since these software systems also change when the production system is reconfigured, the strict assignment of control tasks to specific control units is no longer possible. Instead, generic edge units with standardized interfaces are necessary, which can be used dynamically for any software tasks.

An approach for such a modular control architecture is presented in Fig. 2b. The different levels of the automation pyramid are merged into three levels, which are able to communicate with each other. The lowest level (Cell Level) is responsible for the actual control of the production plant. Units in the cell level are in close contact with the process. In the Cloud Level, computationally intensive and long term processes such as the processing of collected production data, complex, time-consuming simulations and measures for long-term production optimization are carried out. In between is the Shop Floor level. In order to guarantee the flexibility of the production system, it is essential that it is able to execute real-time and fast reaction tasks on the production resources as well as to perform computationally intensive modeling and data processing. The specific tasks that these units perform change dynamically as the production system is modified. Depending on the task, the requirements on reaction time and data volumes change. The edge units on the Shop floor Level are essential for the versatility of the production system.

The described target system corresponds to a decentralized structure, since the computing operations are distributed on the cloud, edge units and intelligent components in the cell level.

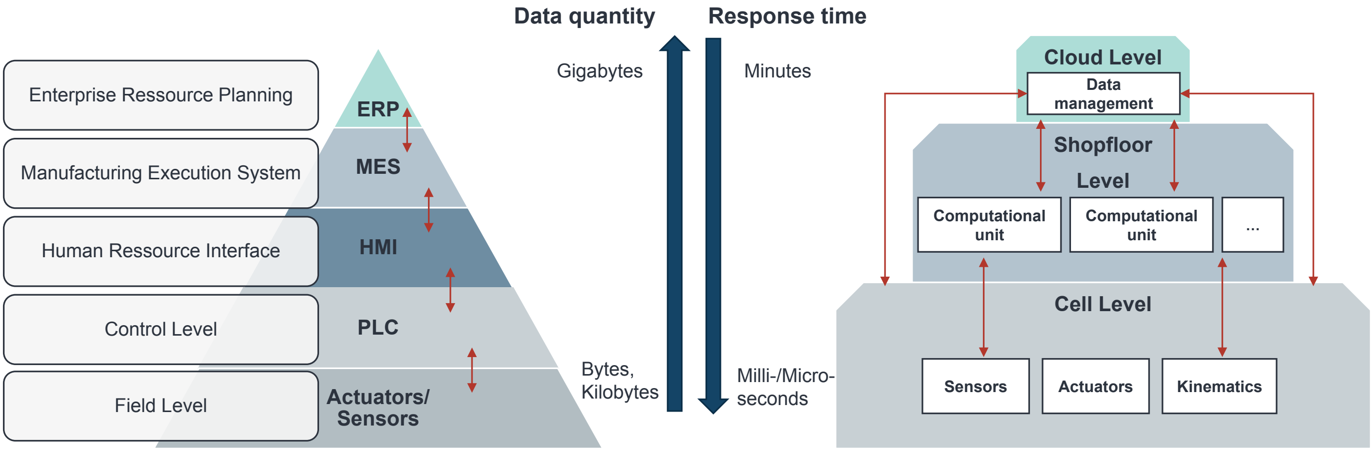

Fig. 2. Status quo automation pyramid (a) and new target system (b)

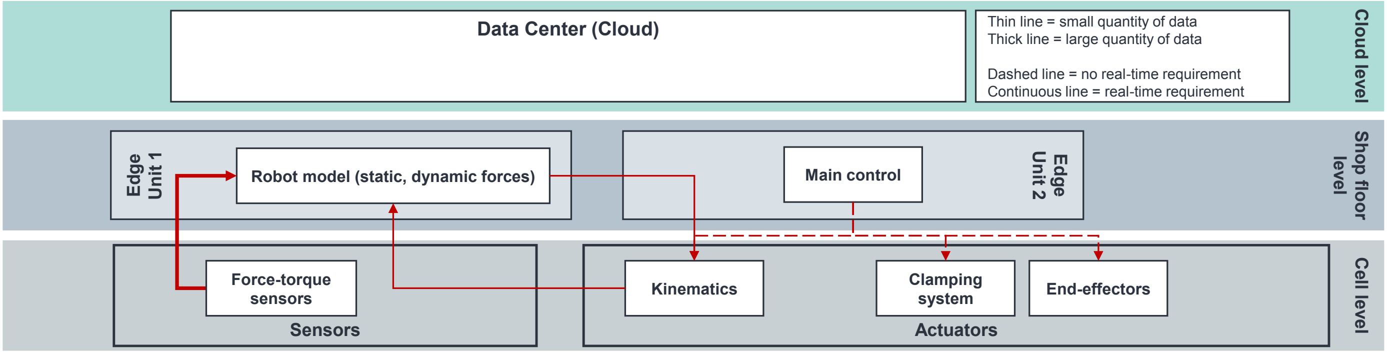

Fig. 3. Control architecture for synchronization of coupled robots

To connect non-intelligent sensors at the cell level with edge units, remote IOs are required. Verification of the robustness of this new target system with respect to the changing requirements of future production systems will be presented in the next chapter.

3. Investigation on the viability of the target system

In the following, the usage of the control architecture presented in the section before will be explained in more detail based on four topics. The first two deals with basic technical functionalities of the WSK concept. The latter two topics, require a functional WSK production system and use it for the execution of two different use cases.

3.1. Coupling and synchronization of robots

In order to meet the typical accuracy requirements in manufacturing, the stiffness of the robot kinematics must be significantly increased. This can be achieved by the mechanical coupling of robots. The coupling of serial kinematics to a parallel kinematic provides a significantly higher stiffness and reduces the influence of the pose on the stiffness of the overall system [4]. This is a unique selling point of WSK and an essential functionality of the production concept. However, rigid coupling of robot kinematics also requires real-time synchronization of the robots. Unlike the geometric coupling of robots, synchronization of two rigidly coupled robots is significantly more complex, as a highly overdetermined system is created [5, 6]. In this highly overdetermined system, the non-ideal motion behaviour of the robot kinematics very quickly leads to stresses called coupling forces. These loads hinder or even completely prevent precise motion of the robots. To avoid this, real-time compensation of the coupling forces during operation is absolutely essential. For this purpose, the total forces and torques occurring at the robot's tool center point are measured using 6-axis force torque sensors.

A force torque sensor is attached between the robot flange and the coupling flange of both robots. However, the loads measured here include not only the coupling forces, but also dynamic and static loads as well as process forces from the manufacturing processes. In order to determine and compensate the actual coupling forces, other partial loads contained in the total measured load must be known. An analytical robot model will be used to calculate these loads in real time. Once these loads are known, the actual coupling forces can be determined at runtime and corrective actions can be initiated to reduce the forces. The accuracy of the determined coupling forces therefore depends on the accuracy of the analytical robot model. However the minimum accuracy required has yet to be examined in experiments.

Position correction values for each individual robot axis are derived from the coupling forces and fed back into the position control system. This feedback takes place without direct influence on the controller, since only the reference value of the position controller will be corrected. The feedback of the coupling forces into the individual axis controls of all twelve axes must be performed in real time. This means that the acquisition and processing of the measured values, the calculation of the dynamic and static loads, the calculation of compensating control variables, and the communication must all be done within the interpolation cycle of the robot control which is usually 2-10 ms.

Modelling of the coupling forces in real time requires high computing power, which the robot controllers cannot provide themselves. Additional edge units are needed that can provide high computational power as well as a fast communication in real-time and with low latency. At the same time, an external edge unit also has to serve as a master controller, coordinating the robots and peripherals, ensuring data exchange and controlling safety functions. The requirements on computing power combined with low latency demand a communication close to the production floor itself. The coupling force model must therefore be performed on independent edge units in the shop floor level. The architecture of this control system, embedded into the target system is presented in Fig. 3. The presented legend for the communication paths is also valid for the following architectures.

3.2. Process-related self-optimization of robots kinematics

As already mentioned, the primary objective of the WSK is to enable the execution of a wide variety of operations, especially machining processes, using several units of a defined robot kinematic. In contrast to classic special machines, such as machine tools, the focus in their development is therefore not on achieving the highest possible static and dynamic stiffness through mechanical design, but on the flexibility of the system. The high stiffnesses that are nevertheless necessary for a wide variety of processes are instead realized by coupling of robot

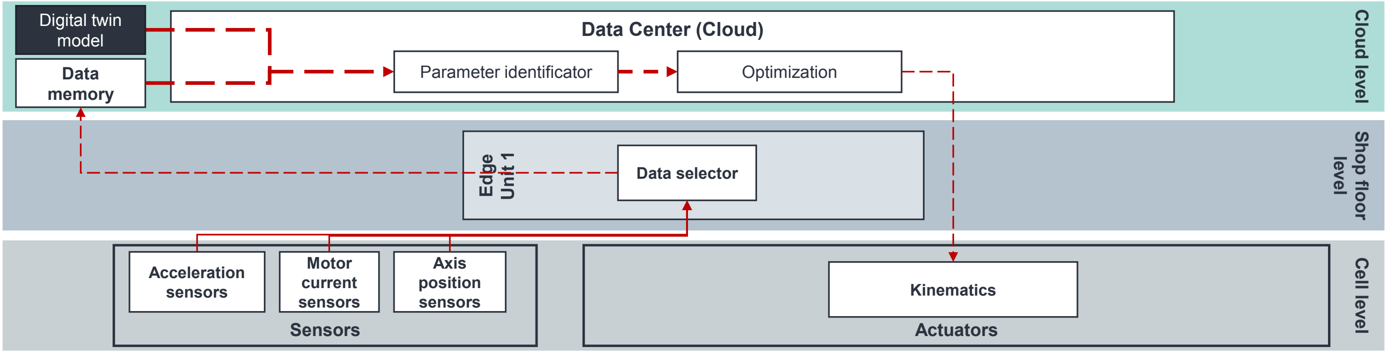

Fig. 4. Control architecture for process-related self-optimization of robots kinematics

kinematics and by using intelligent software algorithms. Examples for such algorithms are the selection of a stiffer pose related to the process force [7] or an adapted parameterization of the drive control [8]. The totality of these actions is referred to in the following as "self-optimization", since each unit optimizes itself according to the present machining and thus exhausts the limit of its mechanical feasibility.

Self-optimization can be divided into two topics. On the one hand, it is necessary to consider the methods that exert an influence on the mechanical properties, such as the choice of poses or the adjustment of the controller parameters (Optimization). However, in order to predict the effect of such optimization actions, the static and dynamic behaviour of the robot kinematics must be known. This means that a digital twin in the form of a mathematical model is needed to enable simulation of the machine behaviour. Since each unit has an individual static and dynamic behaviour and this can also change over time, e.g. due to wear, each unit requires a digital twin that is specially adapted to it and that changes over time. Whereby only the parameterization of the digital twin changes, the mathematical model of the twin always remains the same.

The determination of such a parameter set that changes over time requires the recording of measurement data during operation, which is then evaluated by intelligent algorithms. Both internal machine signals, such as motor currents and axis positions, and measurement data from external sensors, such as acceleration sensors, can be used as data sources. The data acquisition takes place directly on the robot kinematic itself, which means that it must be located at the cell level. As the signals have to be recorded at a high sampling rate, large amounts of data are generated. Thus, a continuous data acquisition is not target-oriented under additional consideration of the multitude of robot kinematics used within a production plant and would exceed any memory capacity. Therefore, algorithms have to be developed, which decide when which data is recorded (Data selector). Due to the necessary fast data transfer, high computing power and intermediate memory capacity, these algorithms are executed on the shop floor level within the edge units available there. The individual data records for various processing operations and machine states must then be stored centrally. In addition, the evaluation based on this data to calculate the desired parameter sets for the digital twin model requires high computing power, but not real-time capability. For the central storage and evaluation of the measurement data, the cloud level is therefore the obvious choice (Parameter identifier). Fig. 4 shows the individual elements and connections on the three levels mentioned.

3.3. CAD-CAM based control architecture for flexible disassembly cell

As the circular economy becomes increasingly important, the associated dismantling of end-of-life goods is coming to the foreground. One of the challenges of dismantling is the diversity of variants, as this is the case for Li-ion battery modules [9]. The requirements for flexible disassembly of goods with high variant diversity can be fulfilled with the WSK, in particular through reconfigurability. A concept for a flexible disassembly cell consisting of two specialized kinematics with interchangeable handling and separation effectors was presented and discussed in [10]. In the following, the control system architecture for Li-ion battery module disassembly based on the target system is presented and the key requirements for the communications between the units are worked out.

Cell units in the given use case as shown in Fig. 5 are for example the robot kinematics, which performs movement actions, separation tools such as a milling motor spindle for separation operations of (undetachable) joints (rivet and weld joints), gripper for handling of disassembled parts or the work piece and a clamping system for fixing the work piece. The main control serves as a moderator and orchestrates the mentioned cell units according to the master-slave principle (Main control = master, cell units = slave) by accessing the cell units' public interfaces. The automated derivation of the control code is based on the virtual model of the product (CAD model). After the product analysis including identification of the components as well as the relations and graph-based (dis)assembly sequence planning, the process planning follows. The result is a list of processes including process parameters, which is the basis for deriving the control code. With the help of camera-based real geometry matching in the machine vision processing, the CAD model can be overlaid with the real 3D object captured by a 3D camera to compute the geometric deformation field and fed back to the robot kinematics in form of offset parameters. This step is required due to geometric uncertainties because of component tolerances and cell respiration (changing of cell thickness [11]). Since Li-ion battery cells contains numerous hazards, the state of the product (e.g. the surface temperature) would need to be

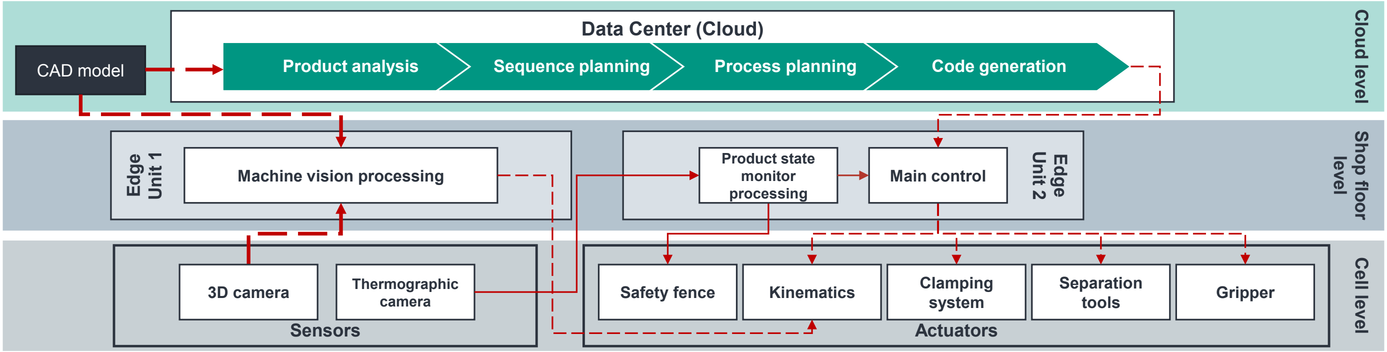

Fig. 5. Control architecture for the flexible disassembly of Li-ion battery modules

monitored for example by a thermographic camera at all times and in case of an emergency case the product state monitor processing gives a locking command to the safety fence for hermetical lock.

In particular, this use case requires a reconfigurable sequence control system where the communication takes place centrally via the main control. Most of the given communication has no real-time requirements except the product state monitoring requiring real-time communication. Except for the communication between 3D camera and machine vision processing, the amount of exchanged data remains on a low level (mainly exchange of configuration and process information). Since the edge units on the shop floor level are responsible for machine vision, product state monitoring and also include the main control, they must process high amounts of data as well as fulfil real-time-requirements.

3.4. Flexible fiber reinforcement of additively manufactured components

In order to handle the trends towards individualization and shorter product life cycles driven by globalization and digitalization in combination with volatile markets, highly flexible manufacturing processes are required. Additive manufacturing has the necessary potential here due to the high freedom of design and individualization, but this potential cannot be fully exploited due to poor and scattered mechanical properties, small component sizes and long process times. The disadvantages are addressed with the use of the WSK, by adding further manufacturing processes to additive manufacturing.

The deficits are already being addressed with different approaches, such as fiber integration to reinforce the components [12, 13] or the use of robotic extrusion systems for the additive manufacturing of large-volume thermoplastic components [14]. To combine the benefits of both approaches, a robot-based experimental facility with the control system architecture based on the target system (see Fig. 2b) is built and represents the use case that will be discussed here.

It consists of two industrial robots (kinematics), a movable print bed and an extrusion end-effector for additive manufacturing and a heating gripper [15], which can produce fiber-reinforced plastic (FRP) preforms in a wide variety of shapes from unidirectional (UD) tape. The collaboration of both robots with the end-effectors and the synchronization with the heating table enables the rapid additive manufacturing of large-volume fiber-reinforced thermoplastic parts. The control architecture planned for the WSK is suited for this highly flexible manufacturing process with a theoretically infinite variety of product variants. As shown in Fig. 6 in the Cloud level, basically the same CAD/CAM chain and control architecture is used as for battery cell disassembly (see Fig. 5).

The general process planning takes place in the cloud level, starting from a CAD model of the desired component. The kinematics, movable print bed, infrared (IR) heater and end-effectors are located in the cell level on the actuator side. The critical process variable of the surface temperature is monitored with a pyrometer and is located on the sensor side within the cell level. As with battery disassembly, an edge unit is also responsible for the main control. In contrast to the battery

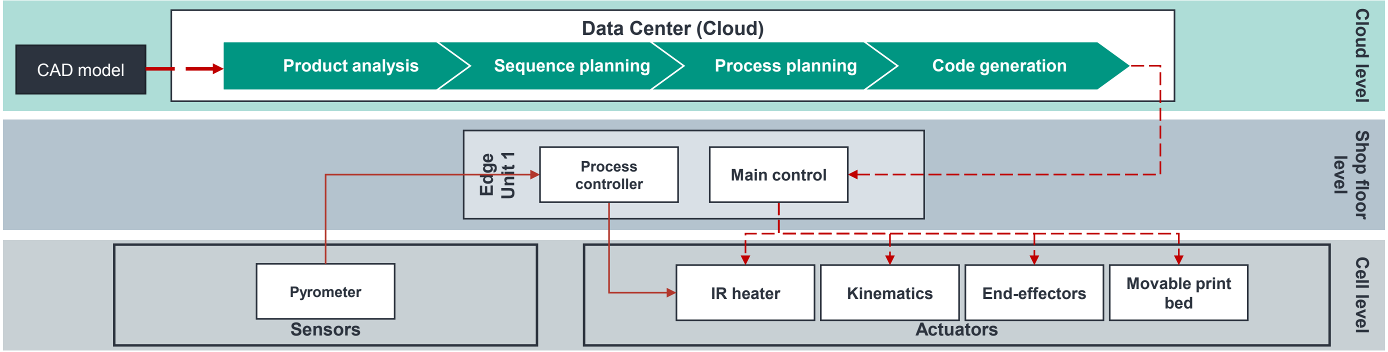

Fig. 6. Control architecture for the flexible fiber reinforcement of additively manufactured components

disassembly, there is no hazardous product here, which means that product state monitoring is not required also product geometry measurement (3D camera) is not used in this use case. Crucial for successful additive manufacturing and reinforcement by preforms is the process variable temperature. If the printed component is too cool before the preforms are inserted, the component must be specifically heated (with an IR heater at the end-effector). This is a process with a real-time requirement, which means that an edge unit is used for process control at the shop floor level.

The presented use case shows that the planned control architecture of WSK can be used for a highly flexible manufacturing process with required real time capability. In comparison to the battery cell disassembly only the edge units have to be adapted.

4. Summary and conclusion

As shown in the given examples future production systems will increasingly use software assistance systems, or in other words services that go beyond the basic controlling of the production machines. A wide range of different services can be used depending on the manufacturing operation. These services differ in terms of their requirements for data volumes to be processed, latency, real-time capability and necessary computing power. For example the services from the shop floor presented in this paper already show a high variation of requirements for data processing. The machine vision processing and the data selector services must deal with large amounts of data while the product state monitoring, process controller and robot model must guarantee real-time capability. Therefore in a constantly changing production system such as the WSK, requirements for the control architecture are also constantly changing. To deal with this uncertainty, the services must be programmed as containers with standardized interfaces that operate independently of the control unit. At the same time, edge units are needed that are not strictly assigned to a task, but instead provide their computing capacity dynamically for a wide variety of shop floor services. These edge units must provide high performance in terms of latency as well as computing power to be able to handle the large number of different services and data processing requirements. This characteristic of the edge units will be essential for the flexibility of the control architecture. Consequently, that means, to secure high flexibility, the disadvantage of oversizing edge units in terms of computational power must be accepted. Furthermore, edge units must be localized close to the production hardware due to the requirements for real-time capability. The overall set of these edge units represent an automation layer (Shop floor Level), which provides the interface between local production hardware (Cell Level) and location-independent production planning and control (Cloud Level), and enables the flexibility of the whole architecture. Although not necessary in the presented use cases a direct link between intelligent sensors in the cell level and the cloud level is conceivable.

In order to implement the presented target system, a modular control architecture with flexibly usable local edge units is necessary. As explained before these units require a basic real-time operating system which should allow to provide computing power dynamically for various services without any detailed knowledge of the actual task. Furthermore, new standardized interfaces and protocols are necessary. The realization of the target system requires further research and development activities. In addition to the development and control of the robot hardware itself, the control architecture and especially the edge units will be another core topic of the WSK research project in the future.

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