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# An approach for a cloud-based machine tool control

Alexander Verl[a], Armin Lechler[a], Stefan Wesner[b], Andreas Kirstädter[c], Jan Schlechtendahl[a]*, Lutz Schubert[d], Sebastian Meier[c]

[a] *Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), Seidenstr.36, 70174 Stuttgart, Germany*
[b] *kiz University of Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany*
[c] *Institute of Communication Networks and Computer Engineering (IKR), Pfaffenwaldring 47, 70569 Stuttgart, Germany*
[d] *High Performance Computing Center Stuttgart (HLRS), Nobelstraße 19, 70569 Stuttgart, Germany*

* Corresponding author. Tel.: +49-711-685-82464; fax: +49-711-685-82808. *E-mail address*: Jan.Schlechtendahl@isw.uni-stuttgart.de.

**Abstract**

Versatility and scalability are the major factors for meeting the requirements of a flexible production of the 21st century. A versatile production can only be realized if the machine control infrastructure is also versatile and scalable – current machine controls are not. Limitations in areas like e.g. reconfiguration ability, security and computational power demand for a radically new concept for machine controls. The approach presented in this paper is to split the physical location of the machine tool control from the machine tool itself. The approach moves the control in a cloud providing machine control as a service (MCaaS).


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## 1. Introduction

Current machine tool controls are limited from a technical viewpoint in different areas like scalability, start-up and reconfiguration time, computational complexity for algorithms and security of the process know-how against unwanted access, to only name some of them.

These limitations demand for a radically new concept for machine controls addressing current and future requirements. The approach presented in this paper intends to split the physical location of the machine tool control from the machine tool itself. The approach moves the control in a cloud providing machine control as a service (MCaaS). This service can be provided by a company-internal service provider (e.g. a machine control department) or outsourced to an external provider. With this approach, the machine control becomes scalable and can handle highly complex computational tasks. Utilizing capabilities of modern Wide Area Network (WAN) and Local Area Network (LAN) communication networks, the machine control is connected with the rest of the machine. For the machine tool owner there is no obvious difference to a conventional machine control. For the machine provider, new business models like hosting and implementing machine control functionality become possible. This approach imposes a couple of difficult challenges demanding an integration of network, cloud computing and machine control expertise.

This paper will introduce the MCaaS approach by outlining the disadvantages machine controls have today in section 2. Section 3 of the paper will focus on the overall system architecture of the proposed cloud-based machine control approach. The derived new challenges in the field of communication methods, cloud operating systems for real time control algorithms and for machine tool modules (e.g. PLC and CNC) are discussed. The paper is concluded with section 4, showing how the proposed concept will be able to address these challenges.

## 2. Disadvantages of modern machine controls

For the automation of machines and plants, various types of controls of different manufacturers are used. These control systems make a decisive contribution

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when it comes to efficient and high-quality manufacturing. For increasing the productivity, manufacturing quality and for mastering complex machines and plants, the control systems have been further developed over the years and represent today powerful but also very complex systems [1].

For users, this development has a positive and a negative side: On the one hand, this allows him to use high-tech machinery and plants for his production and, depending on the application, to select the most appropriate system. Machine manufacturers can integrate their own process know-how, in order to provide the customer with an optimal solution [2]. On the other hand, the operation of these machines presents a major challenge to the user. Whereas the machine manufacturer frequently applies control systems of only one manufacturer and has the necessary experts in his company, the plant operator has to keep a complete machinery plant with different control systems running. If problems occur he either has to have the experts for the respective control systems or request the service engineers of the machine manufacturer which could cause high cost and maybe long downtimes [3]. Solving these problems remotely through telepresence portals is principally possible, but does not always offer the required depth of intervention. Another approach for reducing the risk of downtimes caused by control system problems is to have a redundant control system where the faulty one can substituted. The problem is that redundant systems are not provided as a standard.

Another problem for the user is the protection of the process know-how. Nowadays, everybody who has access to the control hardware can download information from the control, gaining the full knowledge of how the product is manufactured. By buying the same machine, a cheap copy can be created. However, it is difficult to protect machine controls on site against unauthorized accesses. Especially in times of industrial Trojan horses (like Stuxnet) the protection of the process know-how should have priority [4]. Sabotage on-site is another point to be considered. Criminals are able to manipulate the machine in order to create products of bad quality.

These disadvantages in the service and administration area are aggravated by the fact that current control systems are not prepared for the versatile production of tomorrow. Lacking hardware and software interfaces cannot be easily retrofitted and reconfigurability is only possible with considerable additional effort [5]. Besides, the computing power of the machine control is hardly ever completely used in simple applications. If, however, complex controllers, simulations or collision computations should be conducted in parallel with the machining process, the performance of a machine control is not sufficient [6]. Today, the scaling of existing resources is not possible without exchanging the complete control.

Solving the problems stated above creates the need for a new control architecture for machine controls.

## 3. Cloud-based control system architecture

The problems described in section 2 can be solved if the control technology for machine tools is made available where the expert know-how is, namely at the machine tool manufacturer's site or another central point. The machine tools of different users should be provided with machine controls from a data processing center. On site, in the machine tool, only the actuators, which are supplied with nominal values by the distant control, and the sensors, whose actual values are transmitted to the distant control, remain. For the machine tool user there is no difference evident during regular production. The approach will create the control infrastructure as shown in Fig. 1.

With modern safety communication protocols like CIPSafety and PROFIsafe also safety components can be included in the infrastructure as components detect communication errors (e.g. delays, missing and old data) and react according to the specified emergency behavior.

In order to achieve a provision of machine control as a service (MCaaS), further research and networking in the fields of communication technology, cloud real-time operating systems and control engineering is needed.

### *3.1. Communication technology*

In today's machine tools lots of information is transferred between components. This information could be the commanded positions transferred from the control system to the drives but also the actual position which is transferred between drives and the control system. A spindle needs to be fed with a spindle speed, cooling systems provide information about errors and warnings, cooling lubricant pumps need to be enabled and disabled and also warning lights need to be turned on.

Machine tool-internal communication has to satisfy several requirements regarding the interaction between these components consisting of sensors, controls and actuators. Typically, those requirements depend on the application. They can include aspects such as telegram timing and telegram integrity. For instance, an application may only tolerate telegram delay or variation in delay (jitter) to some degree, before the quality of the part manufactured is not acceptable anymore or a failure in a machine component occurs. This could be the case if a drive has not encountered a commanded position for multiple milliseconds, which will cause him to leave the planned trajectory.

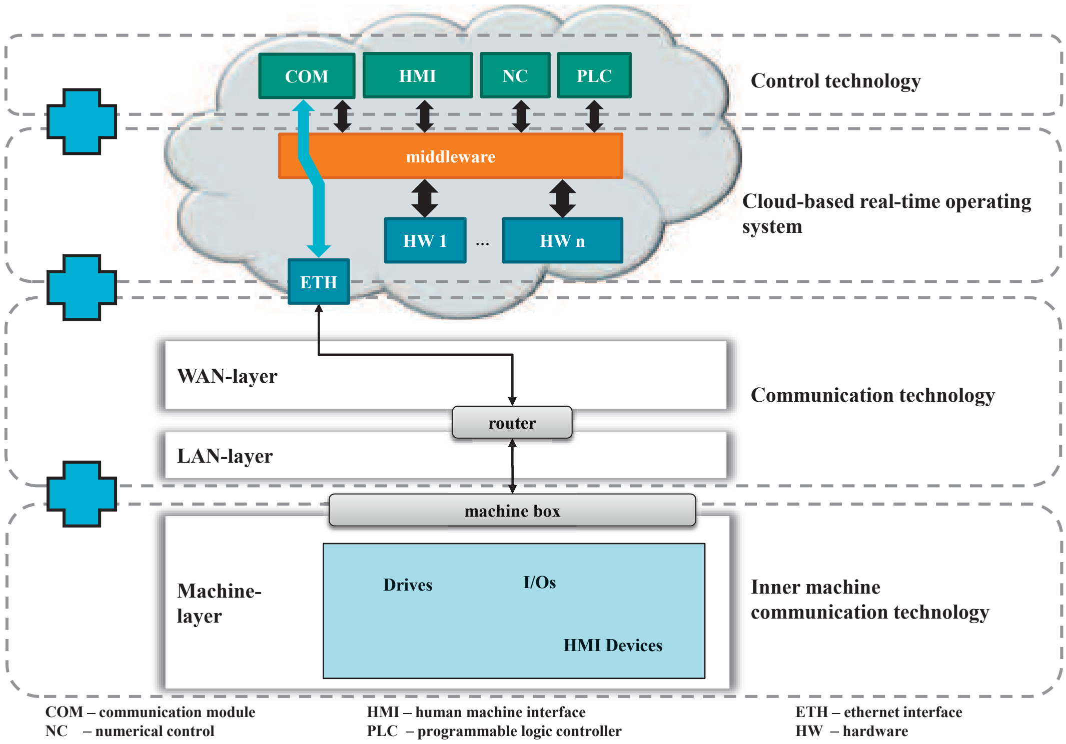


Fig. 1: Architecture cloud-based machine control

For the realization of a cloud-based machine control the requirements of all machine components must be known. To develop this knowledge, fieldbus communication (e.g. drive communication) and other communication (e.g. to the user interface) in the machine tool have to be evaluated in regard to how they react to changing conditions (e.g. telegram errors, jitter and unplanned slow transmission speeds). To do this, the different communication channels in the machine tool have to be identified and classified according to the transferred data volume and latency. For the different communication channels maximal values could then be defined which describe the limit as of which the communication cannot be guaranteed anymore and the application will fail. Then these maximal values have to be adapted with respect to the process currently executed on the machine (e.g. milling) and concerning the basic conditions (e.g. surface quality). A cloud-based machine control has to assure that these maximal values are not exceeded.

The communication over a local area network (LAN) and/or wide area network (WAN) between machine tool and machine control (e.g. PLC and CNC) are under changing conditions. Quality-of-Service (QoS) properties, such as bandwidth, delay and jitter, are hardly controllable, especially in a WAN scenario.

Quality-of-Service properties are not even guaranteed in the case of Best-Effort Internet connectivity, where the network infrastructure is shared between several network subscribers. There exist alternatives such as dedicated fiber-optic infrastructure or leased Virtual Private Networks with Service-Level-Agreement, which can diminish the variability in aforementioned QoS properties to some degree. However, these solutions can be very costly on the one hand. On the other hand, they still are subject to conditions (e.g. fiber cuts) that influence QoS properties.

Therefore, an architecture for enabling real-time communication over a WAN/LAN has to address several major challenges: robustness, reliability and timing. Our goal is to identify strategies and define mechanisms in order to address those challenges. We acknowledge that the properties of the WAN/LAN cannot be controlled completely. Therefore, the architecture has to be able to compensate for effects that are introduced by WAN/LAN communication. Suitable approaches for compensation are a combination of standard strategies (e.g. repetition, buffering) and application-specific strategies (e.g. for milling). By defining these strategies, the maximal values of internal machine communication can be expanded in which a telegram error or an unplanned slow transmission speed does not lead to a communication breakdown and quality criteria (e.g. in regard to surface quality) can be fulfilled at the same time. The strategies have to be reviewed with respect to their influence on the communication and also on the process (e.g. change of quality through repetition of telegrams).

The results have to be implemented in a hardware („machine box") which connects the WAN/LAN layer with the machine layer and also in the communication module of the cloud. The machine layer-facing side of the machine box takes over the role of a fieldbus master, which creates telegrams in a hard real-time cycle for the machine's fieldbus. The WAN/LAN-facing side is responsible for exchanging data with the machine control in the cloud. As the machine box is the connector between the WAN/LAN on the one side and the fieldbus on the other side, it plays an important role for selecting and applying suitable compensation strategies.

For implementing the machine control over a WAN, we propose to rely on existing, well-established standard mechanisms and components. Solutions such as Ethernet/IP, which supports telegram transmission over the TCP/IP protocol stack, may serve as a basis for WAN communication with real-time requirements. GPS-enabled devices can provide accurate time stamp information via NTP [7] or RTP [8] for improved delay monitoring. IPSec [9] can protect the communication against attacks regarding the integrity and secrecy of the telegrams.

### *3.2. Cloud-based real-time operating systems*

In order to overcome the computational limitations of the machine control or meet confidentiality constraints, as described in the section above, the control algorithms, computing and data resources must be moved out of the close proximity of the machine to dedicated and specialized resources. In order to avoid the conflict of either designing the infrastructure to meet peak demands (e.g. to calculate a complex trajectories) or accepting limitations in available resources (similar to the current situation with the internal machine control), on-demand additional resources would be desirable.

This problem is not specific for machine controls and it is faced similarly in every situation where resource demand is not static and elastic increase and decrease of resources on-demand are necessary. This possibility of extending local resources by external ones is known for IT infrastructures as Cloud-bursting [10]. Extending the local resources by specialized external providers is an increasingly adopted concept for outsourcing IT infrastructure in order to reduce operational costs or allow shorter time to market due to decreased provisioning times. The ability to access services delivered remotely also allows to place tasks in the most appropriate environment in terms of compliance with confidentiality constraints or driven by legal requirements.

In order to transfer the Cloud concept to machine control environments, new methods beyond simple virtualization or database management on remote servers are necessary. Only an optimized operating system can address the challenging real-time constraints faced for steering the machines. Such an operating system must be able to find the most appropriate resource and location for a service, thereby respecting the specific requirements in terms of latency, amount of data to be transferred and similar task-dependent information. Finding the optimal allocation of tasks to available local and remote resources is principally very similar to the activities of the kernel in common operating systems. However, classical operating systems are constrained to single computing instances. The operating system proposed has to follow principles of distributed and cloud computing architectures and has to deal with much higher heterogeneity and latencies. Within the Future and Emerging Technologies project "Service Oriented Operating Systems (SoOS)" [11, 12] funded by the European Commission, a concept for a distributed real-time operating system has been elaborated, allowing the distributed execution of applications over different heterogeneous resources connected with varying characteristics. The realized concept can be seen as an attempt to merge parallel computing with distributed computing platforms such as current Clouds. Applications executed on top of SoOS are principally agnostic about which physical resource they are executed on, and single tasks or threads may be dynamically reallocated over time as needed. This also includes the transfer from a local resource such as a computer core to a remote server potentially connected in the local area network or beyond.

The architecture proposed in the context of this paper follows the principles of a SoOS operating system, which builds the basis for realizing an environment for the distribution of the control modules (NC, PLC, HMI, etc.) to the different hardware resources. As the various control modules are allocated to resources on different physical resources, the operating system must guarantee that each module has sufficient computing power and high-speed connectivity (in terms of latency and bandwidth) with other modules and the actuator system of the machine tool. The initial distribution of modules (control systems etc.) may vary over time, based on the actual execution behavior. Principally, the operating system may take historical data or additional constraints defined by the user into consideration, to iteratively improve performance. This also implies that the different control modules must be able to communicate with each other through different protocols and APIs in order to exploit the most efficient communication possible dependent on their proximity. The actual details depend strongly on the distribution of modules across the infrastructure and the implicit availability of communication channels, resource capabilities etc. In order to explore different strategies to be applied and validate concepts for such a distributed operating system, a simulation environment is necessary. SoOSiM [13] is such a simulator and has been originally developed for exploring operating system concepts and operating system modules but can similarly be adapted and applied for the purpose of a distributed machine control. While initially a distribution within a local, rather controlled and predictable environment is targeted with the help of SoOSiM, a wider distribution can be simulated and analyzed.

### *3.3. Control technology*

In control technology a modularization of NC, HMI and PLC e.g. – needed for the distribution in the cloud – is required and an adequate communication profile in regard to the execution of time/communication behavior is necessary (Fig. 2).

As a first step, the communication profile has to be mathematically described so as to enable the cloud-based real-time operating system to calculate the best distribution of machine control modules. The cloud-based real-time operating system must be provided with information about the maximum latency allowed, the communication behavior to be expected (data volume, communication frequency) between the control modules and also about the computing power required, in order to find an optimal mapping of the modules to the infrastructure.

The control modules must be able to communicate also across hardware boundaries through the interfaces provided by the real-time cloud-based operating system. This type of cross-hardware communication does not exist for machine controls today and has yet to be developed.

The best usage of a cloud-based operating system will be possible if different control modules exist that can be distributed over different hardware resources. Here the focus has to be on the modularization of the control according to a granularity that reflects the runtime requirements in a distributed environment. This is the only way to enable a maximum scaling and optimum distribution of the control modules on the cloud hardware with increasing or decreasing requirements on the computing power.

## 4. Advantages of a cloud-based control system

A cloud-based provision of control technology for machine tools eliminates the disadvantages of current integrated controls in the service area. The control can be centrally maintained and administered by qualified staff. Centralization would also considerably reduce the cost of commissioning, maintenance and operation of the machine tool. The same amount of savings known from moving IT infrastructure to a cloud could be expected for machine tools also. Further problems in the machine control can be solved centrally. The same applies to the installation of efficient algorithms for higher productivity; these can also be easily installed on existing machine tools by the control technology provider. Furthermore, this eliminates the need to store hardware for machine controls and the appropriate firmware, in case that the hardware shows a defect or simply has become technically obsolete.

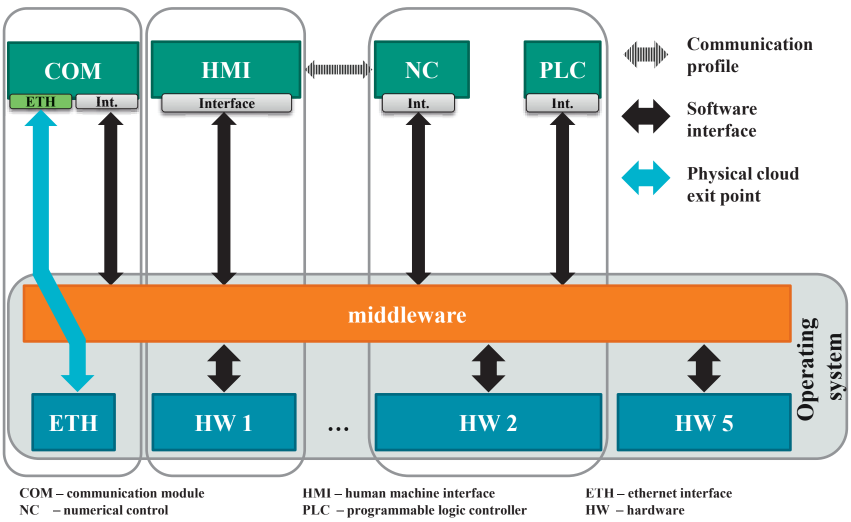


Fig. 2: Cloud-based control system

The centralization of the machine control would also allow for a better protection of the process know-how against unwanted access. A central machine control room can be easier secured against physical access by security systems (e.g. locks, security personal) than control cabinets distributed over a wide area. Focusing on software access: protecting process know-how (located in a cloud and having one channel to communicate with) is easier to protect than process know-how located on many controls, which are all reachable over the enterprise network. An approach to protect process know-how could be based on mechanisms known from IT infrastructure like firewalls, virus scanner and security updates.

In versatile productions a cloud-based provision of controls has two decisive advantages. Firstly, it is possible to scale the performance of the machine controls in order to react to changing requirements. In case of high requirements, however, more capacity and consequently computing power can be provided at short notice due to the elasticity of the cloud resources. Secondly, a spatial change of the machine arrangement will be easier to realize, because there are no hardware interfaces and instead the coupling is solved by software at a central point. Thus the flexibility of the production is considerably increased.

The commissioning of preconfigured applications (e.g. for hardware-in-the-loop simulations and automatic code generations) can be provided centrally. The methods can be tested in advance by the control technology provider. In this case, high computing power is only needed for a short time during commissioning for simulation or compilation purposes. In addition to this, the cloud-based control technology provides the possibility to record measured data centrally; this creates new possibilities for error diagnostics and condition monitoring. Especially in case of complex plants with small quantities it is difficult to establish an adequate data base for running a targeted condition monitoring. By relocating the machine control into the cloud all necessary information is accessible from a central point. And at this central point it is simple to generate a backup of the entire control and to start a reserve system in case of error.

As a summary can be concluded: „Lower cost with higher flexibility: this is one of the major benefits of cloud computing“ [14]. This also applies to the operation of machine controls in the cloud.

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