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ENGINEERING OF MACHINE TOOLS AND MANUFACTURING SYSTEMS USING CYBER-PHYSICAL SYSTEMS

Stefan Scheifele
Oliver Riedel
Günter Pritschow

Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)
University of Stuttgart
Seidenstr. 36
Stuttgart, 70174, GERMANY

ABSTRACT

Today's advanced machine tool and manufacturing system engineering uses mechatronic, system-based modular kits in order to offer machines and manufacturing systems economically. The market increasingly requires not only an economical production of machine tools or manufacturing systems, but also the latest technology, for example, an upgrade or exchange of mechatronic modules. This is economically not possible due to the state of the art.

This paper will present how mechatronic engineering can be developed into an engineering using cyber-physical systems (CPS). It will also present how engineering of machine tools and manufacturing systems will change in the future und which concepts can be realized.

1 INTRODUCTION

Modern production facilities must be rapidly adaptable to changing production orders. This can be achieved by reconfiguring and upgrading, both with respect to the mechanical design and the control system. In order to achieve a rapid customer-specific machine and system configuration, machine tool manufacturers today rely on system-based engineering, which meets various functional requirements with a minimum of resources (Reuter et al. 2010).

2 STATE OF THE ART

Modern machine tool engineering has developed modular concepts and can thus offer economical production facilities for a wide range of manufacturing tasks. Consequently many companies already see the module concept not only as a mechanical one, but also as mechatronic units.

2.1 Modularization of the hardware

Around the year 2000, the idea of configurable machines was developed. A first prototype of a reconfigurable robot system was presented by Pritschow et al. (2003). The goal of modularization into mechatronic components was to allow addition, removal or modification of modules to or from a robot within a short timeframe. It was recognized that the choice of system boundaries of a module determines the complexity of the module interface, as well as the reconfiguration efficiency. The following standardized module interfaces have been identified (Pritschow et al. 2003):

- the mechanical interface, which connects the individual modules,

- the functional interface, which describes the functionality, e.g. 2-axis robot joint with differential joint,
- the energetic interface, which supplies the module with energy,
- the communicative interface, which enables communication between the module and the control system.

Thus, a mechatronic component has as few external interfaces as possible. However, this also means that it is limited to one or several similar functions, such as a gripper, so that the mechatronic component forms a closed, autonomous unit.

With the lessons learned, a standardized definition of modules could be found, regardless of whether they build up a robot, a machine tool or a production system.

2.2 Modularization of the software

With the introduction of the integrated circuit technology and the software language C, advanced controls were developed at the end of the 1980s, based on interchangeable software modules (today they would be called apps). In 1992 this control concept led to the OSACA project (Lutz and Sperling 1997; OSACA Association 2001) funded by the European Union, which is based on the following basic concept: The control system has a uniform software platform with standardized interfaces for interchangeable application modules (AM).

In 2001, a corresponding final report ‘Open Controller Architecture Past, Present and Future’ (Pritschow et al. 2001) was written for CIRP. In essence, the project introduced the object-oriented thinking to the industrial control technology. Unfortunately, the manufacturers could not agree on a uniform class library or on a uniform platform for the integration of the manufacturer-specific application modules. Consequently, the vision of interchangeability was not realizable. Nevertheless, the OSACA idea is today the basis for many modern control systems.

2.3 Joining of software and hardware development disciplines

The developments and findings on the field of software as well as hardware modularization form the basis for mechatronic engineering today. A module is understood as a mechatronic module, which includes mechanics, electrics and software engineering and connects these disciplines inseparably (see VDI guideline 2206 (Verein Deutscher Ingenieure e.V. Juni 2004)).

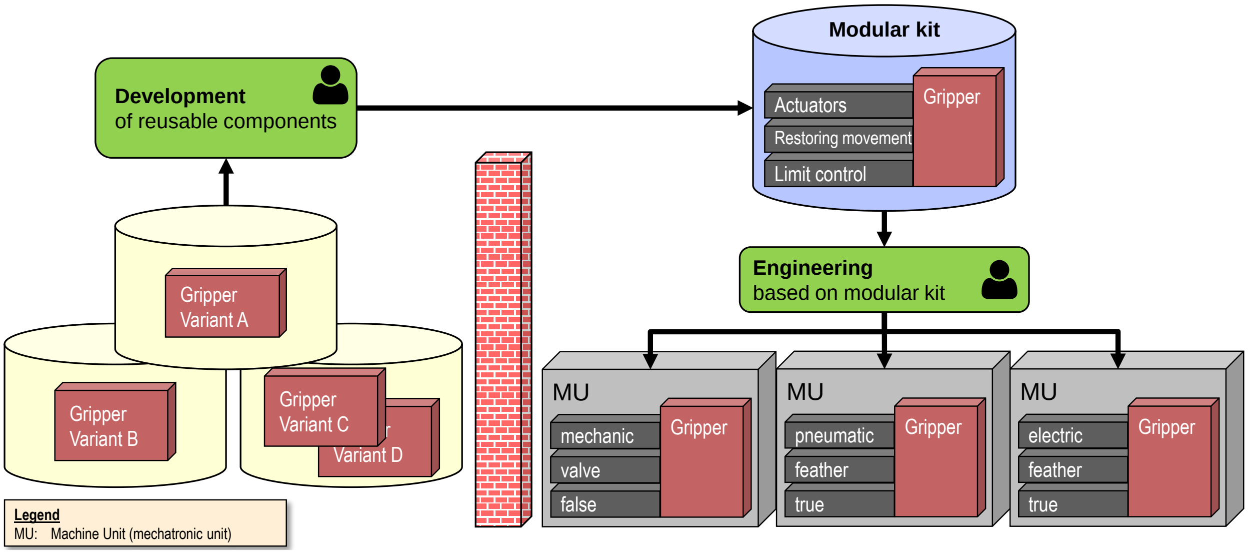

Figure 1: Model of the “Föderal” project (according to Angerbauer et al. 2010)

The procedure model required for mechatronic functional engineering has been developed, among others, within the research projects ‘Föderal’ (2004)(Litto et al. 2004) and ‘AQUIMO’ (2010) (Angerbauer et al. 2010). The engineering process was divided into the two activities ‘development’ and ‘project engineering’. As a result, engineering is required to develop project-neutral, reusable mechatronic components according to predefined standards and to place them in a modular kit (see Figure 1). The resulting modular component has discipline-specific data (parts lists for the mechanics, circuit diagrams for the electrics, program blocks for the software engineering, etc.). During the project engineering order-specific machine based on the resulting construction kit can then be assembled. A complete, cross-disciplinary, mechatronic configuration of the machine is created, which contains all necessary information for the production, software engineering and commissioning as well as all documentation.

In the idealized approach of the mechatronic modules according to Pritschow et al. (2003), the mechatronic modules are closed functional units, which not only contain mechanics, electronics and software, but also have their own control system. Only with such a control cabinet-less concept fast modular interchangeability can be implemented today. Such a concept is used now wherever functionally closed individual machines can be chained to one another via a ‘passage of the workpieces’ (e.g. conveyor and packaging technology, throughfeed machines). A modular robot system, however, is currently not realizable because there is no industrial control solution known capable of coupling independent single axes via a cross-axis path rule.

For this reason, even the most advanced general mechanical and manufacturing system engineering is forced to revert to a control cabinet concept, which means that the mechanics are separated from the electrical system: Most of the I/O interfaces are installed in a central control cabinet, since only the comparatively expensive I/O interfaces can be optimally utilized. Also, the often extensive power electronics of the drive technology is installed here.

However, not only the mechanics and electrics are separated from the mechatronic modules, but also the modular control is, where appropriate, integrated into a central control system. Control engineering dependencies of the individual modules can thus be realized with little effort.

The high complexity associated with this concept can only be managed by engineering tools for the functional engineering according to ‘Föderal’ and ‘AQUIMO’. Because not only is the electrical construction much more complex than in the idealized mechatronic concept, the control programs are also gaining in complexity.

The engineering tools use the functional view of the machine or manufacturing system to be configured. An expert configures the optimal concept for the intended production task based on a construction kit. The generators integrated into the engineering tools then automatically create all necessary documents (e.g. ECAD, MCAD, documentation) for the production of the machine or manufacturing system, configure the CNC and program the PLC of the control system. If logic or functional errors occur during the generation of the control, they remain mostly unknown because of the huge size of such a control program. The commissioning of the machine is usually reduced to the basic functions of safety and functional program for reasons of time, and machine integrity. Thus, most of the control program is not verified.

In order to manage this growing complexity, the virtual commissioning - real control system technology is tested and put into operation on virtual machines - is increasingly supporting the engineering process of the machine tool. A PC simulates the behavior of the real machine in the so-called ‘Hardware-in-the-Loop Simulation’ (HILS) (Pritschow and Röck 2004). The simulation PC must calculate the HILS in the control system cycle time so that the control system is deterministically supplied with fieldbus signals and that it can be ensured that each signal has been recognized and processed. This is the only way to guarantee that the fieldbus behavior of the virtual machine corresponds with that of the real machine.

2.4 Support of mechatronic engineering by virtual methods

Since the early 2000s, research has been investigating the virtual machine. In the beginning, the verification of the control system was of prime importance (Pritschow and Röck 2004; Röck 2007; Wünsch 2007), later modularization and reusability of the virtual machine (VM) in accordance with the insights and procedural models (Kufner 2012; Voß 2012).

Depending on the modelling depth and the objective of the VM, various approaches have been used, ranging from real-time behavioral modelling for virtual commissioning (Verein Deutscher Ingenieure e.V. August 2016) to the non-real-time, realistic image of the physical effects and properties of the machine tool or entire system (Verein Deutscher Ingenieure e.V. Mai 2006).

Various tools for Hardware-in-the-Loop Simulation (HILS) are available on the market. In order to reproduce the time-deterministic fieldbus behavior of the machine tool and thus to be able to work with the original, not manipulated control system, a HILS tool is necessary, which works also time-deterministically and with the control system's cycle time. This is the only way to ensure that the machine tool is simulated without information loss. The only known HILS tool which meets this requirement is ISG-virtuos. With ISG-virtuos, the HILS is primarily subdivided into the behavioral unit (BU) and the geometry unit (GU)(see Figure 2). Together, they build up the virtual module (VU), which is the virtual equivalent of the mechatronic module in the construction kit (Scheifele, S. and Verl, A. 2016b).

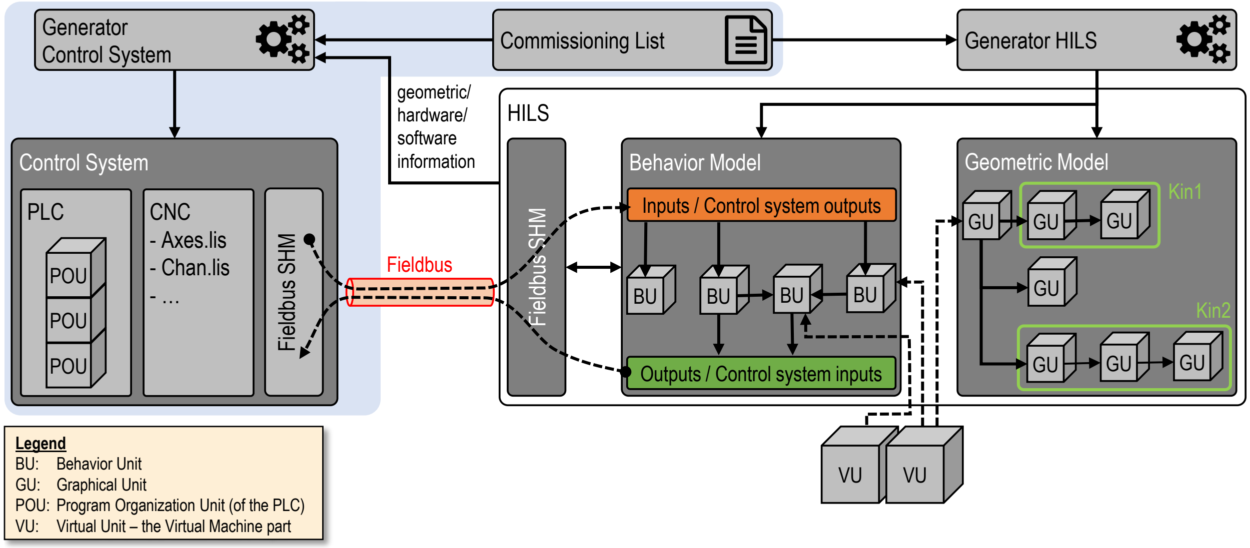

Figure 2: Concept of a Hardware in the Loop Simulation (Scheifele, S. and Verl, A. 2016b)

The practical use of a HILS is countered - at least argumentatively - by the high effort required to create a VM. However, it was shown by the ISW that an automated creation of the VM is possible based on the commissioning list already available for assembling the real machine if the structure is a 1:1 mapping of the real machines module structure (Scheifele, S. and Verl, A. 2016b). Thus, the same rules can be used for the configuration of a VM as for the configuration of a real machine. This creates the economic precondition for testing the control program envisaged for the application. In particular, it is also possible to test failures which could destroy the machine (Pritschow et al. 2005).

2.5 Digest

In recent years, the concepts of the modularization of hardware, as well as of software have been combined into a mechatronic modularization, which allows a uniform view of mechanics, electrics and software. The necessary module interfaces and the methods for modularization and encapsulation of functionality are known. The high complexity of mechatronic machine construction can be managed by engineering tools. With HILS a tool is available, which enables a comprehensive test of the configuration results via engineering tools. Unfortunately, the modular kits used today are heterogeneous for real and virtual machines and control systems. In order to cover these disciplines based on a customer request list, quite different generators and processes have been established.

3 CYBER-PHYSICAL SYSTEMS

According to acatech - Deutsche Akademie der Technikwissenschaften e.V. 2012, Lee 2008 and Verein Deutscher Ingenieure e.V. 2013, a cyber-physical system (CPS) is defined as the combination of software components with mechanical and electronic parts that communicate via a data infrastructure. A CPS is thus a further development of the already known mechatronic component, supplemented by the information concerning this component, such as, for example, the required control system programs and the module description (e.g. the geometry model). This information, which so far has been stored in the construction kit and thus separately from the hardware component, is now coupled with the hardware component. It is stored in a dedicated memory, the ISW calls it the ‘Configuration and Information Memory’ (CIMory) (Scheifele et al. 2015; Scheifele, S. and Verl, A. 2016a), the research project ‘Platform Industry 4.0’ calls it ‘administration shell’ (Zentralverband Elektrotechnik- und Elektronikindustrie e.V. 2015).

The CIMory contains a meta model which describes the CPS. It contains, among other things, the following basic information:

- electrical information (ECAD)
- mechanical design (MCAD)
- program for the PLC (POU)
- configuration for the CNC (CNC Info)
- amount of digital or analogue inputs and outputs
- documentation
- cross-relationships and dependencies with other CPS
- the ‘Digital Twin’ (also called the ‘virtual Unit’ – VU) consisting of the behavior model (BU) and the graphical model (GU) for the virtual machine

Due to the high storage space required it is not possible to store all information directly in the CIMory. In the CIMory, a memory reference (e.g. the hard disk of the control system or a cloud server) can be stored on which the corresponding information can be found.

Figure 3 shows the implementation of the fieldbus hardware of a feed axis CPS. By means of the information stored in the CIMory, the control system not only has knowledge of the amount, the sequence and the types of the field bus terminals, but also of the specific assignment of the outputs and inputs as well as motor parameters and the PLC program (POU) required for the usage of the CPS.

As in the case of mechatronic engineering, a CPS modular kit is used for commissioning a new machine or system. This modular kit is designed according to the rules of object orientation known from computer science. So there are object classes, which are subdivided into object subclasses. These object subclasses are further subdivided into variants and versions of CPSs (Scheifele et al. 2016).

Variants of CPSs result from the adaptation of a solution to different requirements. They are existing side by side. All variants have identical mechanical and electrical interfaces and can thus be interchanged without changing the environment.

Versions are created by changing a variant. They represent the development stages of the variant in chronological order. A new version is necessary if the behavior of the variant is changed. This is done, for example, by mechanically shifting a limit switch of an axis.

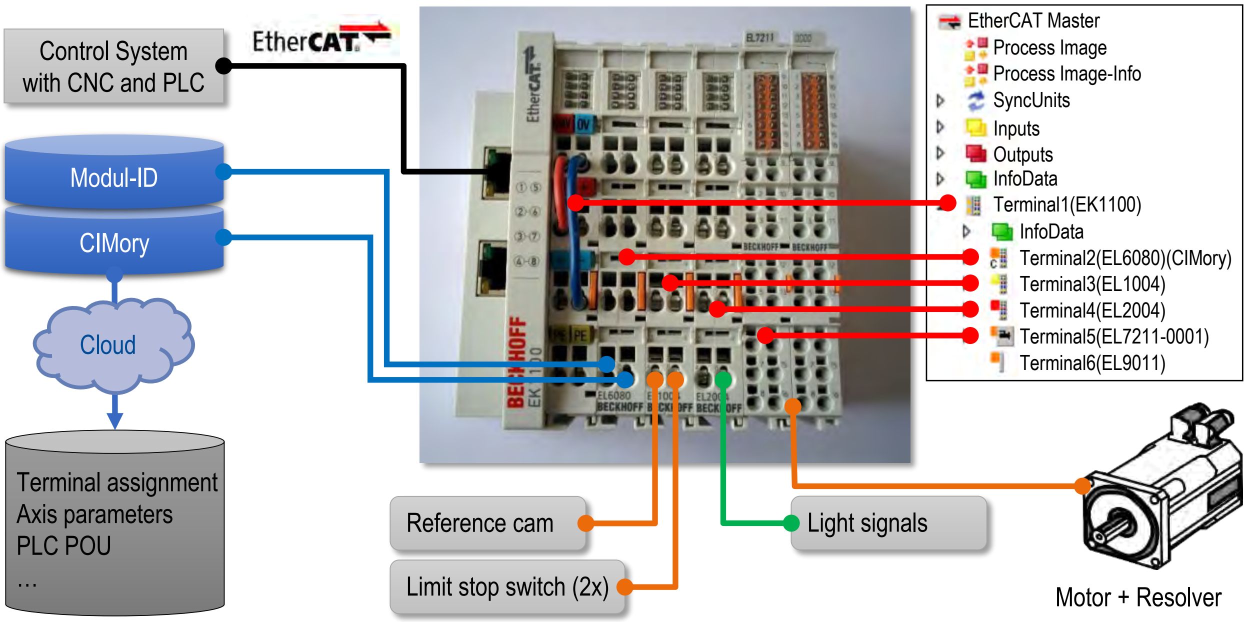

Figure 3: Realization of a feed axis CPS (Scheifele et al. 2016)

3.1 Engineering of a Cyber-Physical Production System (CPPS)

The engineering begins with the customer defining the requirements for the processing task and the framework conditions (e.g., throughput)(see Figure 4). The customer selects the machine type from the machine manufacturer's offer and thus determines the possible scope of functions, working space and possibilities for expansion. Together with the customer, the machine manufacturer can now create a reduced simulation model of the planned machine for a first visual presentation. For this purpose, a configuration tool is used, which supports graphically, script-based or through selection possibilities. The resulting model is to give the customer a first impression of the implementation of his requirement. It needs to be tested against the basic requirements, e.g. working space or interaction with the environment. For this, a simple control, which moves the machine in a state-based manner or by user interaction, is sufficient.

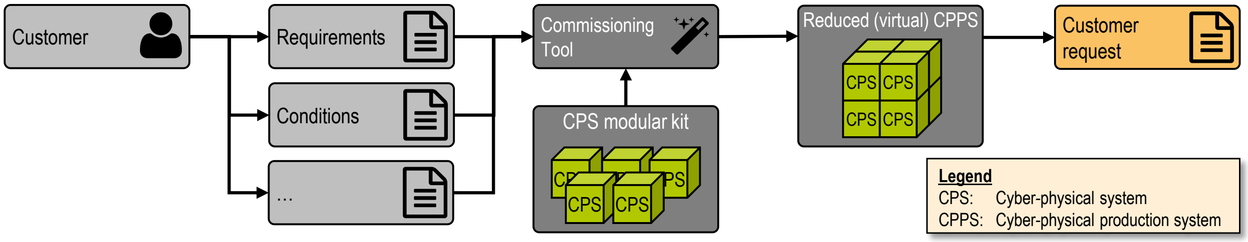

Figure 4: Building a reduced (virtual) CPPS with the customer

If the customer is convinced of his machine, which is specifically adapted for him, the actual configuration of the machine begins. The previously selected CPSs are supplemented by a modular kit for information and the degree of detail of the reduced model is increased, e.g. by specifying the hardware and the software (see Figure 5). The configuration tool also recognizes the existing dependencies and cross-links between the CPSs using the information provided by each CPS. It can add the necessary CPSs to the configuration and exchange already configured ones with more suitable ones. For example, a spindle with a pneumatic tool changer device requires a CPS, which provides the process medium "compressed air" with sufficient pressure and quantity. The configuration tool can select an appropriately dimensioned CPS based on this requirement, as well as on those from other CPSs, which also require this process medium.

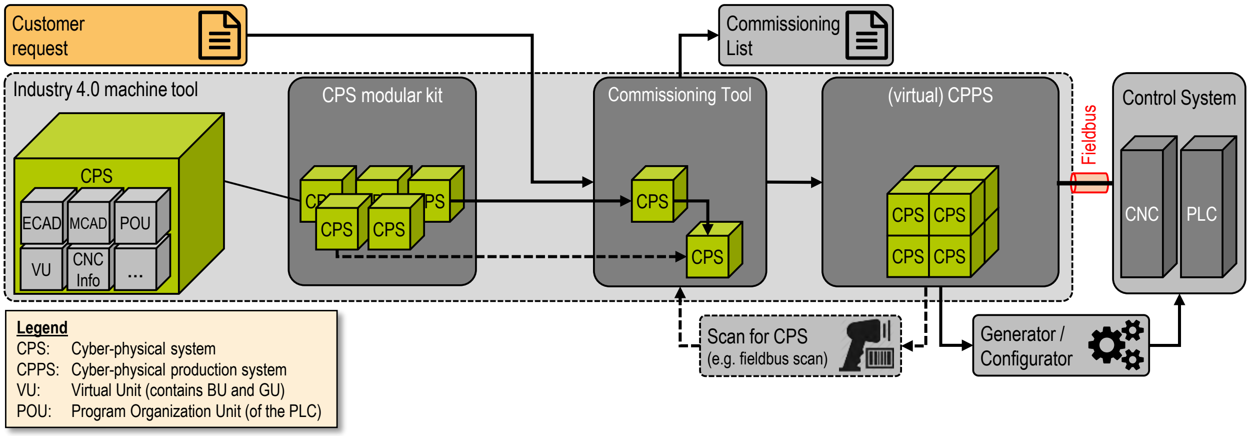

Figure 5: Commissioning process of a CPPS based on a CPS modular kit

Once the commissioning has been completed, a commissioning list is available, which includes all CPSs belonging to the machine. The virtual machine tool, as well as the control system can now be generated, configured and parameterized automatically. (Scheifele et al. 2015, 2016; Scheifele, S. and Verl, A. 2016a, 2016b) Subsequently, a sufficiently detailed HILS is available, on which the control system can be put into operation virtually. All behavioral models of the virtual machine tool are parameterized so that the behavior of the machine is simulated in an idealized way. A first comprehensive test against the requirements and conditions of the customer is possible with the HILS. Likewise, the control system can be fully tested using suitable test cases – according to experts, 2/3 of the PLC program is used for failure detection and primary failure reaction (Pieloth 2013). Tests can also be carried out which identify failures that could result in the destruction of the machine.

In the subsequent Factory Acceptance Test (FAT) carried out using the HILS, the customer confirms compliance with his requirements and general conditions. Since the behavioral model of the virtual machine is similar to that of the real machine the FAT results can be acknowledged. In each control cycle the exact machine behavior is calculated logically correct but a physically correct calculation is also possible (Scheifele, C. and Verl, A. 2016). Once the FAT is passed, the machine is released for production. Automated circuit diagrams (ECAD), production drawings (MCAD) as well as documentation are automatically generated and the machine is manufactured.

As soon as the real machine is available, the fieldbus is scanned. Since all CPSs can communicate with the control system and can identify themselves, a stock list can be set up and compared with the commissioning list. Likewise, the field bus layout and the cabling can be compared to that of the virtual machine being the reference. If the setup of the real machine tool is correct, the real and the virtual fieldbus match. The individual CPSs are then put into operation separately using the HILS. The HILS simulates the behavior of the machine tool. This means that every CPS can be tested individually without any risk. At the same time, the HILS checks the behavioral characteristics of the real CPS and adapts the virtual ones to them. For example, the time required for a cylinder to be extended can be recorded. In the virtual CPS, a minimum and maximum duration is stored for this purpose. A faulty behavior can thus be detected. The mean reaction time of the cylinder is determined by repeated actuation and stored as the actual parameter in the CIMory of the virtual CPS. The virtual CPS and the real CPS then behave identically.

Once all CPSs have been commissioned and the behavior characteristics of the virtual CPSs are equivalent to the real CPS, the machine is ready for production. The virtual machine is then used for parallel simulation in order to detect, e.g. failures and wear at an early stage. Pre-simulation of the production is also conceivable to ensure trouble-free production.

3.2 Modification and upgrade of existing machine tools

If the CPPS was to be modified or upgraded later by new CPSs, this was only possible with great effort: On the one hand, the information on how the machine was constructed and which components were installed were not available. On the other hand, without the information from the manufacturer's modular kit, the control system could not be configured and parameterized automatically - a manual adjustment of the control by a specialist was necessary. Also a software upgrade was so far only possible with high risk. By knowing which CPSs are available in which variant and which version, the previous state could be restored in case of a failure of the upgrade.

Now that all information about the CPS is available in the CIMory, all existing CPSs can be recognized by e.g. a fieldbus scan of the CPPS and the generators can be supplied for the automated generation and configuration of the control system (Scheifele and Lechler 2016; Scheifele, S. and Verl, A. 2016c). Newly added CPSs are detected and automatically recorded in the CPPS, removed CPSs are deleted from the configuration. An economic and automated solution for the conversion and upgrading of existing machine tools is thus realizable.

In addition, it is possible to 'ask' the machine actively for information such as documentation, CAD data or the virtual machine or control configuration. Since the information about each CPS installed in the machine tool is accessible, e.g. via the fieldbus of the machine, programs designed for this purpose like configurators and generators, can acquire the needed information at any time (see Figure 6). All the knowledge about the machine is immediately available.

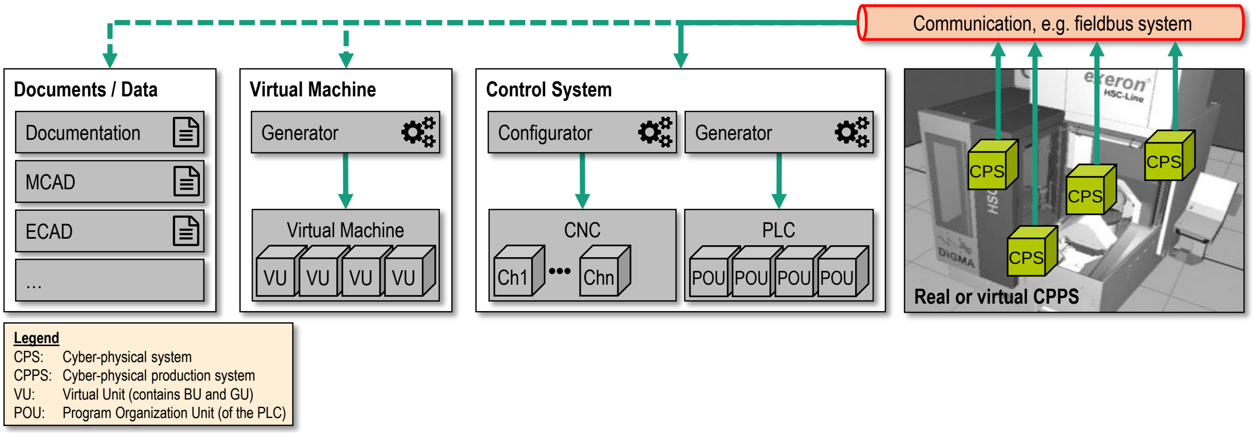

Figure 6: Providing the CPS information via a communication system

3.3 Configuration of control systems

Advanced CNC concepts enable the configuration of a control system through axes and channels. The configuration (and exchange) of building blocks such as 'interpolation', 'lag regulation', 'decoding' is not feasible by the user and also not in demand. Experience shows that all machines can be controlled with the mentioned concept, the 3-axis milling machine as well as the multi-spindle lathe with 20 CNC channels and 180 axes. The axes are described by the so-called machine data record. The assignment of the machine axes (A1) to the coordinates of the programming system (X axis) and then to the interpolation grouping takes place in the channels. Necessary interpolations and transformations and their parameterization are selected by means of control commands of the 'CNC program' (CNC control data, G code program) with the start of workpiece processing. Further dependencies (tool changes, compensation tables) are only loaded together with the processing programs via ‘cycle programs’ and data records.

The kinematic chain, which is obtained in the real machine by the arrangement of the individual CPSs, is represented in a virtual machine by a skeletal model in the same way and with the same interfaces. A skeletal model is often used in CAD systems to describe the relationship between the components. It offers the possibility to consider and to design the CPSs individually. Each CPS contains so-called docking elements to which subsequent CPSs can be attached. Normally, the machine bed is used as a basis point, then the following CPSs are connected to it.

This representation is also found in the control system: Initially only the individual axis-CPSs are known to the control system; they are assigned to a channel and can thus be moved synchronously. There, the so-called transformation (TRAFO) describes the mathematical relationship of the axes to each other. Obviously, if the transformation mathematics can be parameterized via a skeletal model, all three ‘characteristics’ of a machine (control system engineering, mechanical engineering, virtual machine) have the same model structure (see Figure 7). How a control system can be configured and parameterized automatically based on information given by the virtual machine was described by Scheifele and Verl (2016a).

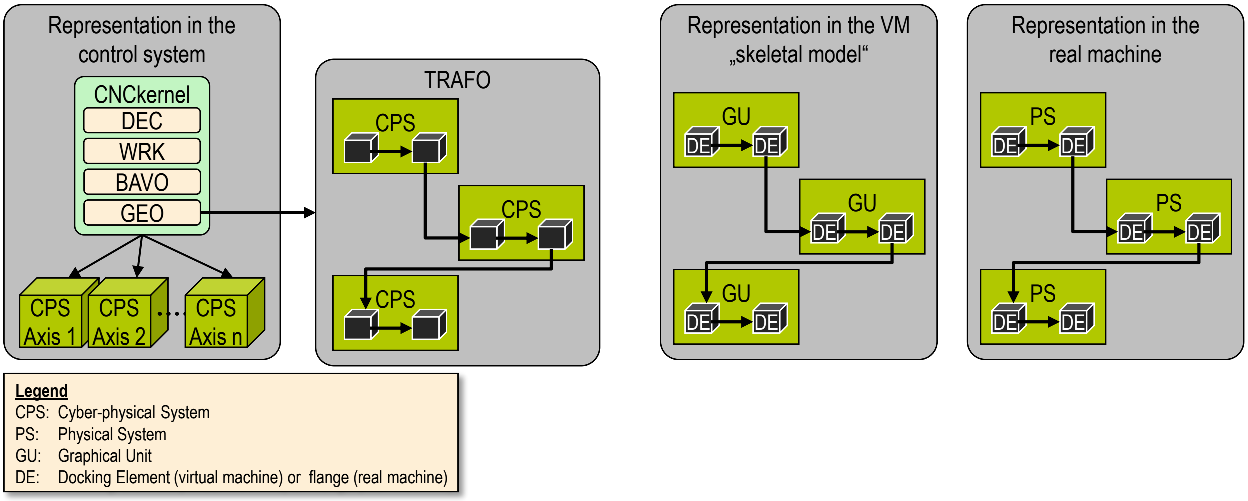

Figure 7: Identical representations of the kinematic chain

3.3.1 Application

Mechanical engineering companies, which already have a mechatronic construction kit and the necessary configuration tools, are interested in further harmonizing the engineering structures and face the challenge of the new discipline ‘Virtual Commissioning’. For these companies it is beneficial to extend their mechatronic modules to CPSs, since this will automatically form uniform structures and the overall design process will become more transparent and economical.

The concept presented in this article for the engineering of modular machines and systems was implemented using a modular demonstration machine: A fieldbus scan identifies the available CPSs and gets their data. An automatic design of the HILS allows the kinematic chains of the machine to be identified. Automatic configuration and parameterization of the control system is then possible. After a successful ramp-up of the control system with the virtual machine, the electrical design of the real machine is checked and put into operation. The machine is ready for production.

The commissioning list of the demonstration machine provides 58 CPSs with a total of 873 I/O, as well as 10 CNC axes in three kinematic chains. Furthermore, several pneumatic PLC axes are modeled. In the model itself the 58 CPSs and another 42 cross-links were linked automatically.

4 SUMMARY AND OUTLOOK

In the context of 'Industry 4.0' the information of the components, which so far has been stored within a construction kit and thus separately from the hardware components, is inseparably connected to the hardware component. It is stored in a memory provided for this purpose. If a machine is subsequently expanded by CPSs, e.g. for a new functionality, the control system of the machine can be configured from the CPSs information provided. Therefore, access to the construction kit is no longer necessary and the control system can be designed automatically.

Within the scope of this research work was found that the description and modeling languages of industry 4.0 available so far, e.g. SysML, AutomationML, RAMI4.0 and eCl@ss, are not sufficient for the workflow presented in chapter 3. In the further course of this research work will, therefore, be examined whether one of the available description languages can be expanded appropriately or a new one must be developed.

The approach presented enables the machine tool or manufacturing system to be tested for customer requirements by means of a HILS and thus even before the real machine is set up. This allows to test different realization possibilities. An optimization procedure adapts the commissioning for a next optimization step by exchanging the CPSs. The implementation that meets the customer requirements best is selected. A workflow that can be integrated into the presented workflow will be developed.

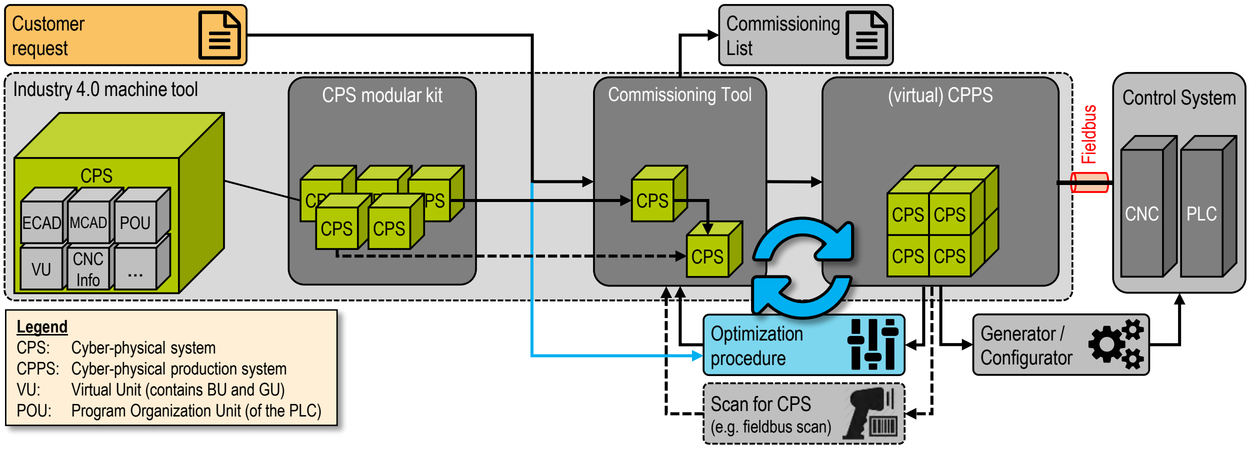

Figure 8: Re-commissioning to optimize the CPPS for the customer's request

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AUTHOR BIOGRAPHIES

STEFAN SCHEIFELE is an research assistant at the Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW) of the University of Stuttgart. Since 2013, he has been working in the field of the economical and automated creation of the digital twin of complex machines and production systems for virtual commissioning by means of software in the loop (SIL) and real-time capable hardware in the loop (HIL) simulations. His e-mail address is stefan.scheifele@isw.uni-stuttgart.de.

OLIVER RIEDEL is Managing Director and Professor at the Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW) of the University of Stuttgart and director at the Fraunhofer Institute for Industrial Engineering (IAO). Prior to joining the University of Stuttgart he held several senior management positions in the IT- and automotive industry. He is also Chairman of the board of the ProSTEP iViP association. His e-mail address is oliver.riedel@isw.uni-stuttgart.de.

GÜNTER PRITSCHOW is an engineering scientist, university professor and former vice president of Acatech. From 1984 to 2005, he was head of the Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW) of the University of Stuttgart. From 1986 to 1990 he was vice-rector for teaching and from 1996 to 2000 rector of this university. His e-mail address is prof.pritschow@isw.uni-stuttgart.de.