Introduction of an Architecture for Flexible Future Process Control Systems as Enabler for Industry 4.0

Michael Gundall*, Calvin Glas*, and Hans D. Schotten*[†]

*German Research Center for Artificial Intelligence GmbH (DFKI),

Kaiserslautern, Germany

[†]Department of Electrical and Computer Engineering, Technische Universität Kaiserslautern,

Kaiserslautern, Germany

Email: {michael.gundall, calvin.glas, hans_dieter.schotten}@dfki.de

Abstract—The term Industry 4.0, which refers to the fourth industrial revolution, aims at the digitalization of industries, including all kinds of production assets. With the help of these, so-called "industrial cyber-physical systems", which form the industrial Internet of Things, numerous novel use cases that are key enabler for a smart manufacturing, can be realized. However, existing facilities mainly consist of legacy equipment and technologies that do not offer these kind of flexibility. To address this issue, we introduce an architecture that allows a flexible reconfiguration and redeployment of future process control systems. Moreover, a high system availability and reliability, as required by industrial applications, has been taken into account. The architectural design follows the 4+1 model approach as it is available in the literature. This ensures, that the design results in a holistic architecture. Additionally, we provide insights into first results and outline future development steps. Index Terms—Industry 4.0, Industrial Internet of Things, Virtualized Process Controller, Architectural Design, Smart Manufacturing, Reconfiguration, Redeployment, Resilience, container

I. INTRODUCTION

A highly flexible manufacturing is seen as one of the most relevant scenarios for factories of the future. Accordingly, the reconfiguration or even redeployment of process controllers in very short intervals, e.g. before each workpiece, is conceivable. In industrial environments, typically programmable logic controllers (PLCs) are used [1]. These controllers are highly sophisticated for continuous control tasks, but typically don't provide any kind of flexibility and have to be stopped, e.g. for deploying an update of the program logic. Hence, they are not suitable to solve this task.

To overcome this issue, the virtualization of process controllers or process control functions is a suitable approach. The virtualization and the application of cloud services are wellknown topics in the information technology (IT), but these days, virtualization concepts are also investigated for industrial applications. Therefore, the authors in [2] carried out a case study for a PC-based virtualized PLC, which was realized on the basis of a virtual machine (VM). The results show that while its implementation is applicable to soft real-time use cases, it lacks hard real-time constraints. With the emerging containerbased virtualization, a promising technology is available that is capable of increasing performance. Consequently, a performance comparison between virtual machines and container virtualization was conducted [3]. In particular Docker container and kernel-based virtual machines (KVMs) were compared. The benchmarks showed that the performance of Docker containers is slightly worse than the performance of native operating system (OS), but better compared to the use of KVM. In addition, [4]-[6] analyzed the use of container technology for the virtualization of industrial automation systems in terms of determinism, real-time (RT) capabilities, performance, and security. For this reason [5], [7] propose architectures for flexible industrial control systems, but limit them to container-based and IEC 61499-based controllers. Based on the findings of [6], which compare the use of bare-metal, VMs, and containers as platform for the virtualization of industrial automation systems, we decided to develop a novel architecture using the 4+1 model [8]. This results, among other things, in a logical view that is technology independent and can be mapped to each of the technologies. Thus, the main contributions of this paper are:

- Introduction of the developed architecture that allows a flexible production, based on most important industrial use cases and their requirements.
- Virtualization strategy that is able to serve as basis for the realization of our concept and its building blocks.

Therefore, the paper is structured as follows: Sec. II describes requirements that serve as basis for our architecture, while the architecture will be detailed in Sec. III. In addition, Sec. IV gives insights about the planned virtualization strategy as well as first results. Finally, Sec. V concludes the paper.

II. FUNCTIONAL REQUIREMENTS

To fulfill industrial use cases and thus realizing a smart manufacturing, [5] identified several functional requirements that must be supported by virtualized industrial automation systems, that have been extended by [7]. The most relevant features for our investigations are explained below.

This research was supported by the German Federal Ministry of Education and Research (BMBF) within the project Tactile Internet 4.0 (TACNET 4.0) under grant number 16KIS0712K. The responsibility for this publication lies with the authors. This is a preprint of a work accepted but not yet published at the IEEE 25rd International Conference on Emerging Technologies and Factory Automation (ETFA). Please cite as: M. Gundall, C. Glas, and H.D. Schotten: "Introduction of an Architecture for Flexible Future Process Control Systems as Enabler for Industry 4.0". In: 2020 IEEE 25rd International Conference on Emerging Technologies and Factory Automation (ETFA), IEEE, 2020.



Figure 1. Technology independent logical view of the proposed architecture

1) Reconfiguration: As already mentioned a high flexibility is required. Therefore, both the firmware of the controller and the user-defined control program have to be updated during operation. This means that the reconfiguration process has to be performed without a downtime of the system.

2) *Redeployment:* The redeployment process is a special case of reconfiguration. In this case, the virtualized industrial automation system must be redeployed during normal operation on another hardware node. This feature is required by mobile devices that may change their location during operation (e.g. change of the factory hall). Furthermore, the case that a system component requires an update or maintenance and is temporarily unavailable is also covered by this feature.

3) Resilience and Self-Healing: Very characteristic for industrial applications are the high demands on availability, which are very different from applications on the office floor. Industrial applications, belonging to the use case group of closed loop motion control, allow only a maximum failure of one minute per year [9]. Since this availability cannot be guaranteed by the equipment of the office floor as a rule, redundancy measures should be taken, whereby the failure of a redundant controller should not affect the process. Since the required redundancy is no longer given after the failure of a system component, an automatic and seamless start of a further redundant instance on a separate hardware node should be triggered.

III. ARCHITECTURE FOR NOVEL VIRTUALIZED INDUSTRIAL AUTOMATION SYSTEMS

This section introduces an architecture that is capable of addressing the needs discussed in the preceding section. Thereby, the design of this architecture should comply with the rules of the 4+1 architectural model [8]. This guideline consists of "4" so-called views (logical view, process view, physical view, and development view) that are used to describe an comprehensive architecture. These views are completed by the scenarios, which are indicated by the "+1", and describe the use case or more finegrained processes of an use case for which the corresponding architecture part is being developed. In the next step, the resulting architecture parts form the overall architecture.

With the help of the logical view, the functional dependencies of entities and their interactions are shown for the specific scenario. After this procedure has been applied to each scenario mentioned above, all dependencies can be represented in a joint figure. The resulting architecture, which is shown in Fig. 1 is explained below using the four scenarios on which the architecture was designed.

A. Start up (Scenario 1)

The start up scenario specifies the procedure for the bootstrapping of the system components. During this process, the VPC Management & Orchestration (M&O) searches for all available Inactive Resources (IRs). An IR can be specified as a component that is in an inactive state but indicates that it has available resources ready for deployment. To keep this information updated, the M&O cyclically sends discovery messages, which can also serve as keep-alive message to indicate a failed IR. When new IRs are available, they register to the M&O. If a Virtual Process Controller (VPC) deployment is requested from the M&O, it determines the most appropriate IR, sets it active (VPC_1) and transfers the configuration data to it. Additionally, the Virtual Process Control Functions (VPFs) that are executed by the VPC are downloaded from the VPF Registry. The specific VPFs can be executed either cyclically or acyclically, and their complexity can vary depending on each application and use case. Based on the required availability, this procedure is repeated for a defined number of inactive VPCs that serve as a backup. In this case one inactive VPC is assumed (VPC_2) .

B. Normal operation (Scenario 2)

This scenario describes the state in which the system runs without errors and no events, such as reconfiguration or redeployment, occurred. The VPC waits for the incoming process data of the industrial cyber-physical systems (ICPSs), performs the tasks in the assigned VPFs and sends the control data back. The special feature here is that all VPCs, both inactive and active, receive and process the data values, but only the active unit transmits output values to the actuators to ensure that the inactive VPC can take over this task in case of a failure of the active one. This requires a precise time and state synchronization of these components.

C. Replacement (Scenario 3)

This scenario describes how to ensure interruption-free operation of the entire system in case of a failure of one of the VPCs. Since the simultaneous failure of the active and all inactive VPCs is not considered, two cases are covered. In the first case, the failure of one of the inactive VPCs is considered. A malfunction of an inactive VPC or an interruption of the communication link due to a failure of the infrastructure would be detected by the active one by the missing response to the synchronization message. In this situation, the active VPC requests the M&O to create a new backup facility to ensure the required reliability. If a suitable IR is available, the M&O will promote it to an inactive VPC. If the active VPC fails, the inactive VPCs recognize this by the absence of the synchronization message. In this case, a predefined inactive VPC will be automatically promoted to be the active one. In the next step, the now active VPC instructs the M&O to replace the inactive one, similar to the failure of the inactive unit. If only a failure of the communication link between the two entities is responsible for the missing message, the inactive VPC incorrectly assumes the failure of the active VPC and incorrectly promotes itself. If the device is completely disconnected from the network due to infrastructure failure, this condition will not affect the system. However, in all other cases, the M&O would be informed of the problem by a double status message from both active VPCs and disable one of them.

D. Reconfiguration and Redeployment (Scenario 4)

If a reconfiguration or redeployment is triggered, the M&O searches for available IRs, selects the two most appropriate ones, and promotes them to VPC_3 and VPC_4 . Once they have completed their startup processes, the M&O triggers the handover between the previously active VPC_1 and the from now on active VPC_3 for a given date. Consequently, these two VPCs should be highly time synchronized. Eventually, the obsolete VPCs are no longer needed and are released.

IV. VIRTUALIZATION STRATEGY

A key task is to determine which virtualization technology can be used to benefit from the proposed architecture. As mentioned above, there are several ongoing activities on this topic, with [3] suggesting that virtualization in the industrial Internet of Things (IIoT) using containers is more appropriate than VMs in terms of memory utilization, latency, and redeployment. However, there are still applications where the use of VMs [6] is preferable. Based on the fact that we want to address RT applications, including high determinism and low latency, we first map the proposed architecture to container technology. Starting from the results in [6], where several network configurations were compared, we expect that the macvlan driver is well suited 3

for industrial use. Major reasons for this assumption are the performance, which is comparable to bare-metal, an automated deployment using Swarm services and the fact that each of the containers has its own MAC and IP address. Thus, each container appears as a physical device and has the possibility to use both, layer 2 (L2) and layer 3 (L3) communcation. To test the performance of our concept, we use the testbed shown in Fig. 2 as the basis for several tests, where the used hardware is listed in Tab. I.

Table I HARDWARE CONFIGURATIONS

Equipment	QTY	Specification
Mini PC	2	Intel i7-8809G, 32 GB DDR4,
		Intel i210-AT & i219-LM NICs,
		Linux 4.19.103-rt42
Network Switch	1	8-Port Ethernet Switch
TSN Eval. Kit	1	RAPID-TSNEK-V0001,
		IEEE 802.1AS-REV

As we investigate first of all if time critical applications can be fulfilled by the applied virtualization, we will concentrate on the communication between VPC and ICPS and between VPCs. Due to the fact that there are scenarios where it is preferable that both VPCs are on the same server to avoid an additional network, and scenarios where VPCs must be distributed across multiple servers, the testbed includes two hosts connected by an 8-port network switch. In addition, Host 1 runs two containers $(VPC_1 \text{ and } VPC_3)$ to simulate Scenario 4, and Host 2 runs a third container, which can be either VPC_2 (Scenario 3) or an ICPS (Scenario 2). To use automatic IP assignment by Docker and to avoid address conflicts, each host has its own /24 subnet. With this configuration, each host is capable of running 253 containers. Since the end-to-end (E2E) latency of communication between the components is to be determined so that performance and determinism of the framework can be evaluated, both hosts must be time-synchronized. Therefore each host is connected to a shared IEEE 802.1AS grandmaster and runs the ptp4l service, which is part of Linux PTP. Linux PTP¹ is a free and open source gPTP implementation that complies with the IEEE 802.1AS standard. By using this implementation, a synchronization accuracy of <1µs between both hosts can be guaranteed. To validate the better performance of the macvlan network driver, we compare it to the bridge driver, i.e. the standard configuration of Docker containers, and bare-metal. In addition, the use of messages based directly on the MAC layer (L2) has several advantages over the use of the IP layer (L3), such as reduced packet size and faster packet processing. For this reason, the E2E latency measurements are performed for both L2 and L3 communications. The results of the tests are shown in Fig. 3 and Fig. 4.

Several conclusions can be derived from both figures. First, the maximum values of the E2E latency for bare-metal and macvlan differ only slightly. Furthermore, the E2E latency of packet transmission at L2 is $\approx 40 \mu s$ lower, compared to L3. In

¹Further information: http://linuxptp.sourceforge.net/



Figure 2. Testbed configuration for a first evaluation of our virtualization strategy of the proposed architecture



Figure 3. E2E latency for applications and containers within a single host.



Figure 4. E2E latency for applications and containers across hosts.

V. CONCLUSION

The introduction of virtualization concepts makes it possible to redeploy and reconfigure future industrial automation addition, a macvlan network is $\approx 30\mu$ s faster at L2 and $\approx 40\mu$ s faster at L3 compared to a bridge network. This means that transferring messages on L2 using the macvlan network driver in one direction can save $\approx 60 - 70\mu$ s compared to the standard Docker network driver. Since most time-critical use cases, such as closed loop motion control, require bilateral message exchange within a single loop, the time saving is already more than 120 μ s. This leads to the conclusion that for time-critical communication between VPCs, such as state synchronization, where no routing is required, the use of L2 macvlan networks is suitable.

systems. In this paper we presented a novel architecture that addresses these challenges. Based on the modelling rules of the 4+1 model, we built the architecture from four views and four scenarios. In addition, first insights into the intended virtualization and realization of the architecture are given and initial performance benchmarks for the planned virtualization are presented.

REFERENCES

- P. Gaj, J. Jasperneite, and M. Felser, "Computer Communication Within Industrial Distributed Environment—a Survey," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 182–189, Feb. 2013. DOI: 10. 1109/TII.2012.2209668.
- [2] O. Givehchi, J. Imtiaz, H. Trsek, and J. Jasperneite, "Control-as-a-service from the cloud: A case study for using virtualized PLCs," in 2014 10th IEEE Workshop on Factory Communication Systems (WFCS 2014), May 2014, pp. 1–4. DOI: 10.1109/WFCS.2014.6837587.
- [3] W. Felter, A. Ferreira, R. Rajamony, and J. Rubio, "An updated performance comparison of virtual machines and Linux containers," in 2015 IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS), Mar. 2015, pp. 171–172. DOI: 10.1109/ISPASS.2015. 7095802.
- [4] A. Moga, T. Sivanthi, and C. Franke, "OS-Level Virtualization for Industrial Automation Systems: Are We There Yet?" In *Proceedings of the 31st Annual ACM Symposium on Applied Computing*, ser. SAC '16, Pisa, Italy: Association for Computing Machinery, 2016, pp. 1838–1843. DOI: 10.1145/2851613.2851737. [Online]. Available: https://doi.org/10.1145/ 2851613.2851737.
- [5] T. Goldschmidt, S. Hauck-Stattelmann, S. Malakuti, and S. Grüner, "Container-based architecture for flexible industrial control applications," *Journal of Systems Architecture*, vol. 84, pp. 28–36, 2018.
- [6] M. Gundall, D. Reti, and H. D. Schotten, "Application of Virtualization Technologies in Novel Industrial Automation: Catalyst or Show-Stopper?" In Preprint: 2020 IEEE 18th International Conference on Industrial Informatics (INDIN), 2020.
- [7] S. Grüner, S. Malakuti, J. Schmitt, T. Terzimehic, M. Wenger, and H. Elfaham, "Alternatives for Flexible Deployment Architectures in Industrial Automation Systems," in 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), vol. 1, Sep. 2018, pp. 35–42. DOI: 10.1109/ETFA.2018.8502526.
- [8] P. B. Kruchten, "The 4+1 View Model of architecture," *IEEE Software*, vol. 12, no. 6, pp. 42–50, Nov. 1995. DOI: 10.1109/52.469759.
- [9] M. Gundall, J. Schneider, H. D. Schotten, M. Aleksy, D. Schulz, N. Franchi, N. Schwarzenberg, C. Markwart, R. Halfmann, P. Rost, D. Wübben, A. Neumann, M. Düngen, T. Neugebauer, R. Blunk, M. Kus, and J. Grießbach, "5G as Enabler for Industrie 4.0 Use Cases: Challenges and Concepts," in 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), vol. 1, Sep. 2018, pp. 1401–1408. DOI: 10.1109/ETFA.2018.8502649.