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Dynamic reconfiguration of service-oriented resources in cyber–physical production systems by a process-independent approach with multiple criteria and multiple resource management operations

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HIGHLIGHTS

- Fog/Edge- and Cloud-based Approach.
- Unified Modeling Approach.
- Multiple Criteria and Multiple Degrees of Freedom.
- Dynamic Service Embedment.
- Dynamic Service Placement.

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ABSTRACT

During the last years, the convergence of classical automation and modern information technology within cyber–physical production systems is an ongoing process. With this development, service-oriented architectures and technologies of Fog/edge and Cloud computing are now moving into the next generations of production systems. However, these innovations also create new challenges in terms of complexity and fragility. In order to ensure reliable production operation, it is necessary to adapt to any disruptions and disturbances caused by system-internal or external events. This leads to a dynamic reconfiguration of both, the operational technology and the services including the dependent information technology. The goal of this paper is to provide a system- and process-independent method for the dynamic evaluation, embedment and placement of services on the processing IT resources of a cyber–physical production system during operation. For this purpose, both production- and IT-specific requirements and properties of all resource elements involved are mapped in a unified formal system description. This includes the individual process steps as part of process control, the necessary services and their dependencies as well as the processing IT resources such as computing nodes and transmission links in the field, Fog/edge and Cloud. For the evaluation and comparison of different combinations, a suitable multi-criteria evaluation metric is defined and used for resource configuration. The unified modeling and evaluation of process steps and services enables a dynamic embedment of the most suitable available services for each individual process step. In addition, modeling and evaluating of services and processing IT resources enables services to be dynamically placed on the most appropriate IT resources. The result is a system of service embedments and placements in a heterogeneous system landscape that adapts dynamically to production- and IT-specific events. The validation of the approach is based on a case study in which dynamic changes of a process engineering production process are examined and discussed. This shows how the reliability of production in dynamically changing system landscapes can be increased.

1. Introduction

Service-oriented architectures form the foundation of cyber–physical production systems (CPPS) [1,2]. CPPS represent a specialization of general CPS [3–5]. One group of CPPS focuses on

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operational technology (OT). A CPPS consists of a physical plant as well of a virtual domain including system models and control functionality. Therefore, many dependencies of requirements of the physical plant to the virtual domain arise. Fog/Edge and Cloud Computing complement the existing architecture of field devices with two additional pillars [1,4]. Fixed, hierarchical structures are replaced by decentralized and dynamically changing, highly heterogeneous resource landscapes. The driving force leading in this direction is the convergence of classical automation technology and modern information technology [5,6]. Currently existing simultaneous developments of these two worlds are merging as a direct result of the increasing IP-based networking and service-oriented architectures [7–10]. This convergence opens up many new possibilities, such as direct access from a web application to any sensors in the field. These possibilities enable completely new potentials of flexibility and optimization as well as enabling completely new business cases. However, as heterogeneity and dynamics in the resource landscape increase, so does the complexity and fragility of the overall system. Mastering these requires completely new ways of dealing with unforeseen events which can be caused by internal or external causes. On the one hand, such production systems require capabilities for the independent detection and resolution of problems on a level that is independent of the plant and the specific production process, and on the other hand reacts very specifically to its requirements, characteristics and current capabilities. Just as modern data centers react to failing mass storage devices or network nodes, production systems have to recognize unforeseen situations in the process, the plant and its environment as well as in control and information technology and correct them fully automatically. A dynamic adaptation of existing IT resources, i.e. services, computing nodes and transmission links to new requirements can be a valuable building block. The goal of the paper is to provide a system- and process-independent method, which increases the requirement fulfillment of the cyber–physical production system (CPPS) by dynamic evaluation, embedment and placement of the services on the existing computing nodes in the field, the Fog and in the Cloud. This supports dynamically required functional elements and models and exploits the existing heterogeneous IT infrastructure in the best possible way. In Section 3 the state of the art and in Section 4 the service management problem is described, regarding the application in CPPS. The method described is an extension and specialization of the approach described in [11].

The dynamic management processes are carried out by a unified formal system description, which is formalized in Section 5.2, taking into account the requirements, properties and capabilities of all resource elements involved. In the formalized system description, both production and IT-relevant aspects are modeled in a unified way. This includes models of the process control, the available services and their dependencies as well as models of the logical computing nodes and transmission links across the domains field, Fog/edge and Cloud. In Section 5.3, a multi-criteria evaluation metric is specified, which allows the individual analysis and comparison of different resource combinations at runtime. Section 6.3.1 introduces an algorithm that evaluates the most suitable service instance for a given production step and dynamically embeds them into the production step on the basis of the unified modeling and evaluation. Finally, in Section 6.3.2, an algorithm for the dynamic placement of services on the most appropriate logical computing nodes is described as a complementing resource operation, depending on the link- and node-specific properties. In Section 7, the exemplary evaluation of the presented approach is performed with the help of a case study from the field of process engineering in process industry. In Section 8, the results achieved with respect to the fulfillment of requirements are finally discussed and compared with unmanaged approaches.

2. Service-oriented architecture for the considered Fog/Cloud-based CPPS

Describing the architectural characteristics and requirements of the considered Fog/Cloud-based CPPS, the mean elements of the SOA must be introduced:

- The production system is designed as a service-oriented architecture. That means, logical resource elements described below are encapsulated as services.
- The production system consists of the two main domains IT infrastructure (with processing nodes and transmission links, service network including control services and their dependencies) and the OT domain with sequence control including production steps and step transitions).
- The three main system domains are assumed to be loosely coupled among each other, in order to allow dynamic reconfiguration at runtime.
- Given the points above, a chain of dependencies exists between the modules in the field, the production steps defined for the respective module, the control services required for this and the IT infrastructures required for the services. Generally, this point is illustrated in Fig. 1.
- The IT infrastructure consists of heterogeneous elements distributed over the field, Fog and Cloud level, corresponding to the RAMI 4.0 hierarchy levels (IEC-62264, 61512).
- The service network consists of heterogeneous elements and forms a complex meshed structure according to the RAMI 4.0-Layer and the service Cloud in VDI/VDE-Position Paper [4].

In the following, the requirements regarding the dynamic service management are described. These are derived from the above architectural characteristics and can be related to one or more of the main system domains process, IT infrastructure and service network, as well as the interfacing points between those domains. The structural requirements of the considered CPPS are:

- Heterogeneous IT infrastructure elements such as logical processing nodes and transmission links of the Field, Fog and Cloud level are mapped and handled uniformly
- Heterogeneous service instances and their mutual dependencies across the different abstraction layers (RAMI 4.0 hierarchy level, IEC-62264, IEC-61512) are mapped and handled uniformly
- Field-specific constraints that are caused by local dependencies such as input/output interfaces for sensors and actuators as well as Smart Objects or other assets are mapped and handled uniformly

Further, the dynamical requirements of the considered CPPS are:

- Dynamic addition, removal or modification of one or more production steps and their requirements or properties
- Dynamic addition, removal or modification of quality of service parameters (QoS) of service instances (functional elements) and their dependencies
- Dynamic addition, removal or modification of quality of service parameters (QoS) of logical processing nodes and transmission links

Furthermore, the requirements of the generated service composition are:

- As a result, a dynamically optimized mapping of process steps to service instances (control functionalities), the so-called process step-to-service instance mapping is necessary