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5G as Key Technology for Networked Factories: Application of Vertical-specific Network Services for Enabling Flexible Smart Manufacturing

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***Abstract*—In recent years, the interest in interconnecting production machines has grown and new technologies such as augmented reality enter the shop floor. This evolution is driven by hyped topics such as Industry 4.0 and Internet of Things. These topics promise benefits through increasing transparency in factories, such as improvement in efficiency and reduced costs, e.g., due to data analysis. As a result, the demand on new concepts and technologies for factory networks is rising to fulfill the upcoming new requirements. Therefore, the development of 5G comes just in time. This paper is focused on one of the 5G core technologies network function virtualization (NFV). We propose two use cases that demonstrate how NFV enables flexible smart manufacturing. In NFV technology, virtual network functions (VNF) are composed to network services. We introduce the application of our vertical-specific network services that enable augmented reality on-demand and the flexible interconnection of production machines with services in company's cloud backend.**

I. Introduction

For nearly a decade, Industry 4.0, Internet of Things (IoT) and Industrial IoT (IIoT) are hype topics, which have in common that entities, such as machines and/or other devices, are interconnected. The interconnection of machines makes machine data available and often more easy accessible. Additional wireless sensors offer further data. Machine data and additional sensor data complements business data from enterprise resource planning (ERP) systems. The data can be used to create dashboards showing the current status of all machines and its key performance indicators (KPI) in real-time, such as the overall equipment effectiveness (OEE). This fosters the transparency, paper-based offline reports become obsolete and decisions can be taken earlier. Furthermore, it enables data analysis; e.g., for enabling predictive maintenance to reduce not foreseen machine downtimes and therefore costs; and it can be used by production engineers for optimizing the machine utilization and the delivery performance. Those arguments are clear indicators that the interest in factory data is on the rise.

In addition, mobile devices and new technologies such as augmented reality (AR) enter the shop floor. Tablets are used as modern human-machine-interfaces (HMI) and smart glasses are used in production environments to train technical staffs and enable remote support of machines. For example, Weidmüller already uses the Microsoft HoloLens (see Fig. 1) for world-wide remote maintenance of machines and factory inspections, which reduce technical staff's and inspector's travel time and therefore costs.

Fig. 1. Application of Microsoft HoloLens for remote maintenance of an injection molding machine's tool at Weidmüller Group

New devices and new data make the factory more transparent and knowledge on-demand available. This supports workers and managers, but the upcoming new data sources and data sinks increase the data traffic in already existing factory networks significantly. Therefore, high data throughput and low latency become essential for modern producing companies, and in addition, networks need to be more flexible and scalable. Regularly, new machines and their devices are added to the shop floor and therefore to the network, and existing machines are moved on the shop floor because production lines are reorganized. As a result, the company's factory network is regularly reorganized. This takes time and costs and it is error-prone due to human interaction. Additionally, the growing use of AR devices makes network planning more complex because the need for network resources is significantly increased, but often just for the duration of the usage. This indicates that new network concepts and technologies are necessary.

The 5G Infrastructure Public Private Partnership (5G-PPP) has identified the "factories of the future" as one of the vertical sectors that are most important for 5G, and addresses the needs described above by the 5G targets in its white papers [1] [2]. This indicates that 5G might fulfill current and upcoming needs of networked factories. One emerging technology that enables 5G is network function virtualization (NFV). In this paper we focus on NFV rather than on the advances in the radio part of 5G. NFV replaces network functions on dedicated appliances (e.g., router, load balancer) by virtual instances defined by software running on commercial of-the-shelf (COTS) hardware. These functions are called virtual network functions (VNF) and increase network's degree of flexibility significantly.

In previous work [3], a first concept for a practical smart manufacturing use case was proposed. Requirements were presented that must be fulfilled by network services which are applied in such use cases and VNFs needed were introduced. In this paper, the concept is detailed and applied. VNFs are implemented and deployed. We present vertical-specific network services that enable augmented reality on-demand and the flexible interconnection of production machines, e.g., with MES/ERP and/or services in company's cloud backend. We describe two use cases in Section II applying such network services, and detail the envisioned architecture and involved components in Section III. Finally, we conclude our contribution in Section IV and give an outlook on future development.

II. Use Cases

We describe two use cases in this paper that demonstrate the flexibility and scalability of networks due to network services: machine interconnection and augmented reality on-demand.

A. Machine Interconnection

The starting point of the machine interconnection use case is the creation of a new machine park. We assume that the network infrastructure and a factory network are already available; business and management systems such as an ERP and a manufacturing execution system (MES) are installed and usable; an Internet uplink is present for cloud computing; and a network function virtualization infrastructure point-of-presence (NFVI-PoP) is already running on a co-located server. As an example, a new injection molding machine (IMM) shall be integrated into the factory network for providing machine status information and allowing machine control. Therefore, its network interface must be configured.

A simple option in order to do this is using the Dynamic Host Configuration Protocol (DHCP). It is well-known from corporate and consumer IT systems and could be used to dynamically assign IP addresses to all machines and devices on the shop floor. However, a concept is necessary to avoid that unknown devices can be integrated because unknown devices are always risk factors for cyber security. In addition, subnetworks are often consciously used on the shop floor to segment the factory network; e.g., an own subnet is useful per production machine and/or per production line. The factory network segmentation reduces the network reconfiguration effort when machines are moved because the host addresses inside the subnetwork are not affected. Furthermore, network segmentation is an important part of the cyber security concept for factory networks and well-defined network rules are essential. Therefore, static network configurations, firewalls and network address translation (NAT) are often used in factory networks. For this purpose, production machines/lines are equipped with industrial Ethernet devices such as switches and routers that provide network functions such as NAT, routing and firewalling. In addition to this, an intrusion detection system (IDS) could also be useful to detect threats.

In this use case particular network functions are implemented as virtual network functions (VNFs). These VNFs are combined with further use case specific VNFs and are composed to vertical-specific network services (NS): the factory edge network service (NS1) and the machine interconnection network service (NS2). NS1 is instantiated once per machine park to collect data and forward it to the MES, ERP and an externally hosted cloud backend. NS2 is instantiated once per machine and connects it to the machine park's network and especially to NS1. The data flow through the network services is illustrated in Figure 2, but the architecture of the network services is detailed in Section III.

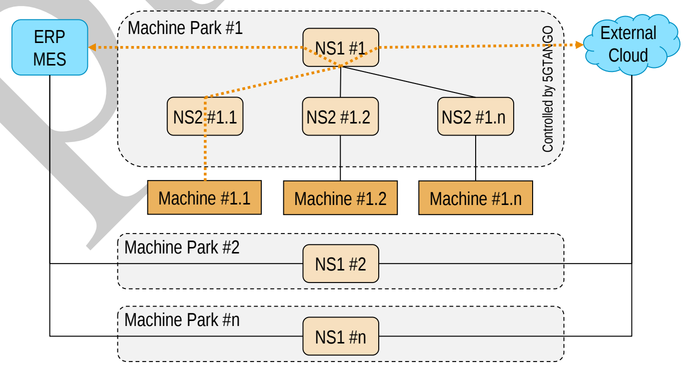


Fig. 2. Dataflow in a network service based smart manufacturing architecture

When the new machine was physically connected to the machine park, the machine needs its initial network configuration via a configuration screen because DHCP is not selected. A factory management portal (FMP) is instantiated once per NFVI-PoP and manages the vertical-specific network services. The machine interconnection concept bases on three steps when NS1 is already instantiated:

1) The technical staff creates a new machine in the portal. The portal generates all necessary information for the network configuration of the physical machine and initiate an instance of NS2 for this machine.
2) The technical staff uses the configuration information generated by the portal to configure the machine's interface. This includes the network interface, i.e., IP address, subnet mask, DNS, Gateway address as well as machine-specific communication protocol configurations. Using

the example of Euromap 63 [4] these are: the network path to the session folder used for Euromap 63 communication and the corresponding user credentials.
3) Finally, the technical staff confirms the successful deployment using the FMP.

B. Augmented Reality on-demand

The focus of this use case is on the provision of a service (augmented reality) on-demand; i.e., the network resources needed are started on-demand as well. We assume that the molding machine, that was integrated in the previous section, is running and a technical staff plans a routine maintenance using smart glasses, such as the Microsoft HoloLens, as maintenance support tool. In a first scenario, the technical staff plans a routine maintenance without remote maintenance support, but with support of visualized machine data. As described in the previous section, machine data is transported using the network services NS1 and NS2. In a second scenario, the technical staff that does the maintenance is supported/guided by another technical staff who is the machine expert but located in another country. The technical staff that does the maintenance is shown in Figure 1. Figure 3 shows the display of the supporting technical staff. He watches the maintenance process and sees the same view the HoloLens user is seeing. The technical staffs can work together in the augmented reality; e.g., they can set arrows and mark points of interest to enhance the communication. The procedure to realize the two scenarios is illustrated in Figure 4.

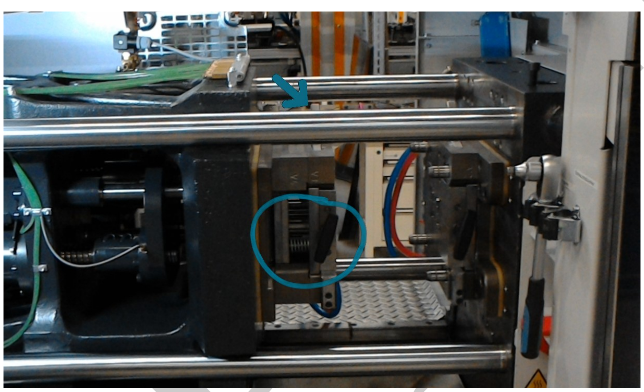


Fig. 3. Positioning of markers during remote maintenance of an injection molding machine's tool using Microsoft HoloLens and Skype

1) The technical staff that does the maintenance triggers the instantiation of NS3: the AR maintenance network service. This is done by pressing the appropriate button "start maintenance mode" in the FMP.
2) NS3 contains a router that interconnects the local access point with the Internet and enables the Internet connection of the Microsoft HoloLens on-demand.
   a) In the first scenario the Microsoft HoloLens is used to visualize machine data. This is done by dashboards created in Microsoft Power BI[1].
   b) In the second scenario the Microsoft HoloLens is used as a remote maintenance tool. The telecommunications application Skype is used.
3) When the maintenance is finished the technical staff that did the maintenance terminates NS3 by pressing the appropriate button "stop maintenance mode" in the FMP. As a result, the Internet connection is terminated.

[1] https://powerbi.microsoft.com/en-us/

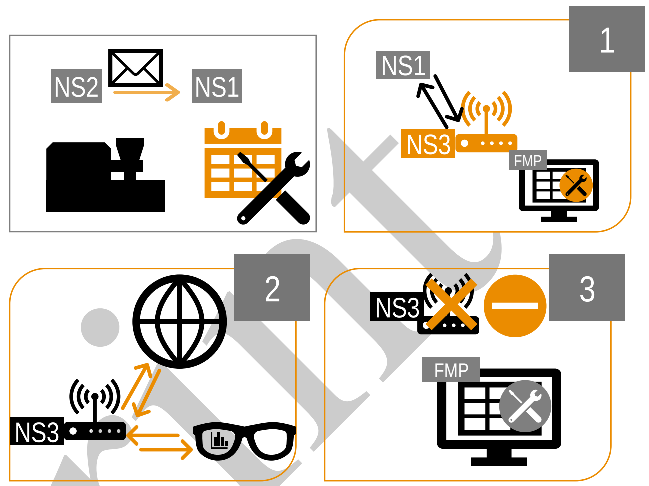


Fig. 4. Procedure for augmented reality on-demand

In the next section, the architectures of the network services and the VNFs are detailed.

III. Architecture

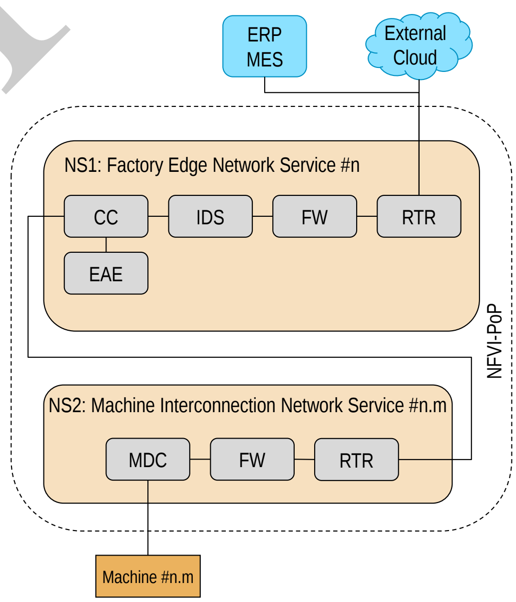


Fig. 5. Architecture of the vertical-specific network services

As described in Section II, three network services are used. The architectures of the factory edge network service (NS1) and the machine interconnection network service (NS2) are illustrated in Figure 5. NS1 consists of five VNFs: the router

VNF (RTR) that routes traffic to other networks, the firewall VNF (FW) that controls the traffic, an instance of an intrusion detection system (IDS) that detects threats, the cloud connector (CC) that forwards data received to the MES, ERP and an externally hosted cloud backend, and the edge analytics engine (EAE) that process/analyze data on edge.

NS2 consists of three VNFs: the router VNF (RTR) that routes the traffic to NS1 and allows to use dedicated network segments for each machine; the firewall VNF (FW) that controls the traffic; and the machine data collector (MDC) that forwards data from the machine to the CC. The MDC is described in more detail in Section III-A and the CC in Section III-B.

NS3 consists of a router VNF (RTR) that routes traffic on-demand from the HoloLens to the Internet to enable Skype calls for remote maintenance and data visualization via Power BI dashboards or reports. NS3 is only instantiated on-demand.

A. Machine data collector (MDC)

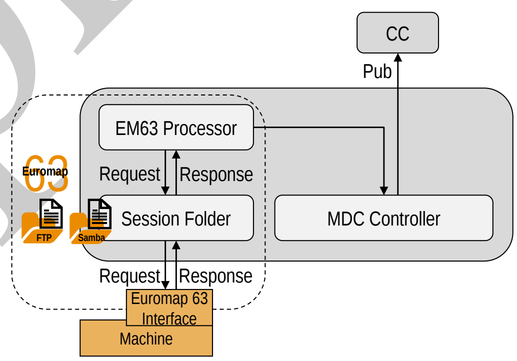
The machine data collector (MDC) consists of two modules: the Euromap 63 (EM63) Processor and the MDC Controller. Its architecture is shown in Figure 6a. The MDC Controller works as an MQTT client and publishes data to an MQTT broker which is part of the Cloud Connector (CC) VNF. MQTT (Message Queuing Telemetry Transport) [5] is a lightweight IoT protocol. It uses the messaging pattern publish-subscribe and works over TCP/IP. The Paho Python Client[2] of the Eclipse Paho project[3] is used as MQTT client implementation.

The EM63 Processor manages the data transfer with the injection molding machine using Euromap 63 [4], a file based data exchange standard. The MDC instantiates a session folder which is shared with the machine. Its path and the user credentials have been generated by the factory management portal (FMP) and were entered in the machine during its configuration. The file exchange protocol used is depending on the machine type. For example, the protocol server message block (SMB) as well as the file transfer protocol (FTP) are frequently used. For this purpose, the MDC provides a samba server (or alternatively an FTP server).

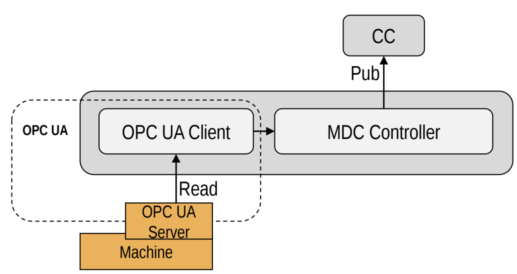
We apply the message exchange pattern request-response. This means, that the MDC creates a session request file and a job file and writes both files into the session folder. The machine is looking for these files. The request file commands the machine to execute the job file. The job file is a report request and lists all the parameters that have to be reported by the machine. The machine processes these files and writes both files the corresponding session response file and the report response file into the session folder. The session response file signals that the request was processed or not. The report response file lists the parameters requested for report and the corresponding parameter values. The MDC is looking for these files, process them and forwards the data extracted.

The file based data exchange standard Euromap 63 is outdated because Euromap 77 [6], a new standard that bases on OPC UA [7], was released and replaces it. However, Euromap 63 will still be relevant for the next years because of the long service life of an IMM. Nevertheless, an OPC UA module for the MDC VNF is necessary because OPC UA became a popular standard for industrial communication.

The Reference Architecture Model Industrie 4.0 (RAMI 4.0) is described in [8] and specified in [9]. It refers to OPC UA as approach for implementation of a communication layer, but Industry 4.0 communication based on OPC UA is also found on the information layer where OPC UA's information models are located [10]. The increasing number of OPC UA companion specifications indicates that OPC UA is accepted by a wide range of users from various industries. For example, Euromap 77 [6] describes the interface between IMM and MES; a specification was created by a joint working group of the OPC Foundation and PLCopen that defines an OPC UA information model to represent the IEC 61131-3 architectural models [11]; and umati (universal machine tool interface) is an OPC UA companion specification for universal communication of machine tools towards external communication partners, e.g., MES, ERP, cloud, automation system etc., that is in development [12] [13]. Therefore, Figure 6b illustrates the architecture of the MDC VNF using an OPC UA interface for machine communication but its implementation is beyond the scope of this paper and will be part of future work.



(a) MDC VNF using file exchange via Samba or FTP



(b) MDC VNF using server client concept of OPC UA

Fig. 6. Architecture of the machine data connector (MDC) VNF

B. Cloud Connector (CC)

The key objective of the cloud connector (CC) VNF is to collect, aggregate and forward data which is generated by the machines and collected through the MDC. The CC VNF consists of three elements: the broker, the processor and the

[2]https://www.eclipse.org/paho/clients/python/

[3]https://www.eclipse.org/paho/

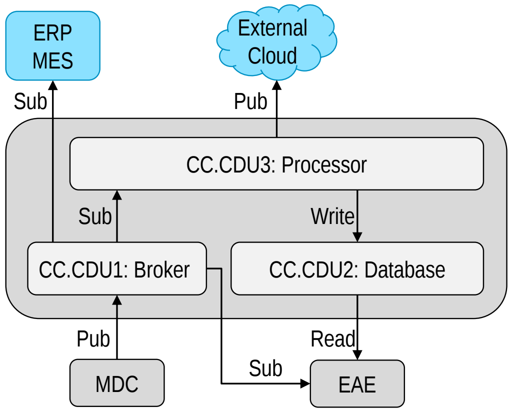


Fig. 7. Architecture of the cloud connector (CC) VNF (part of NS1)

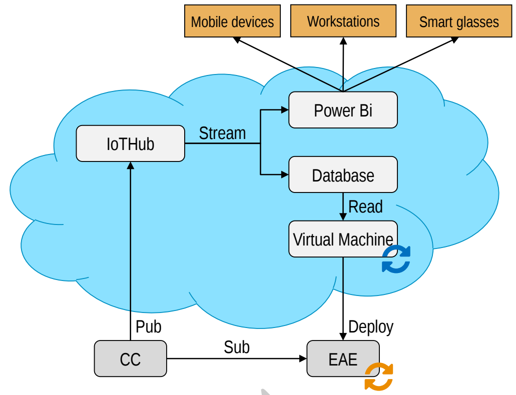


Fig. 8. Interconnection of edge and cloud computing applications

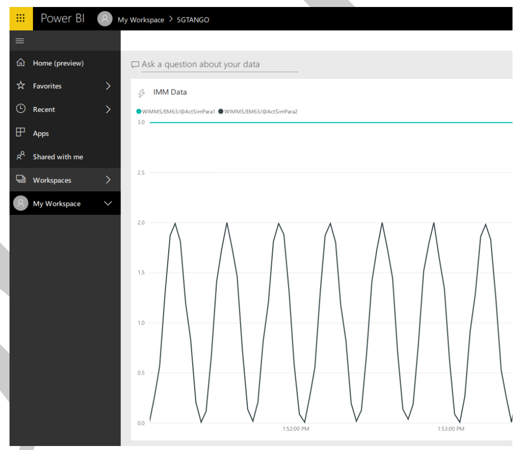


Fig. 9. Dashboard in Microsoft Power BI showing two data sets

database. These are single containers and so called cloud-native deployment units (CDU). Its architecture is shown in Figure 7. We decided to use Mosquitto[4] as MQTT broker solution, because of the good documentation, lightweight code base, and existing Docker[5]-based containerization solutions. The processor, the edge analytics engine (EAE) and the MES/ERP can subscribe from Mosquitto. The processor (CDU3) subscribes from the broker (CDU1) and publishes data to the cloud backend that is detailed in Section III-C and writes data into the time series database (CDU2), so that EAE can also use historical data within a short time period for data analysis. If SAP's MES/ERP solution is used, the SAP Plant Connectivity (SAP PCo[6]) can be used for data exchange; i.e., SAP PCo subscribes from MQTT broker and forwards data to the SAP system using agent instances [14] [15].

C. Cloud backend

The envisaged cloud backend architecture is shown in Figure 8. We decided to use the cloud computing service Microsoft Azure, but the concept is not restricted to it because the CC VNF uses the MQTT protocol to publish data into the cloud, so that other cloud computing services supporting MQTT could also be used. The Microsoft IoTHub[7] receives the data published by the CC. It is a managed cloud service that is the central data hub between applications and devices. A stream analytics job is created that forwards data to Microsoft Power BI, where data is visualized in dashboards and reports. Figure 9 shows such a dashboard. It visualizes two data sets generated by our injection molding machine simulator (IMMS): a static value and a periodically changing value.

The IMMS is used for test purposes and represents the machines in our prototype (see Figure 5). Its communication interface Euromap 63 works similar to a physical IMM's illustrated in Figure 6a. The IMMS is implemented in Python and a web-based graphical user interface is used to control it. The IMMS was designed for upcoming scalability tests because only very few physical machines are available for tests.

D. Deployment

The VNFs are implemented as lightweight Docker containers. The 5GTANGO NFV descriptor format is used to describe the network services (based on the VNFs) and the 5GTANGO network service and VNF package format was used for packaging.

The network services and VNFs have been successfully implemented and deployed on 5GTANGO's rapid prototyping platform vim-emu [16]. The constant value and the periodically changing value are generated by the IMMS. The values are forwarded by the factory edge network service (NS1) and the machine interconnection network service (NS2) to the Power BI dashboard shown in Figure 9. The successful data transfer proves the successful implementation and deployment.

IV. Conclusion & Outlook

This paper presents one of the first NFV-based smart manufacturing proof-of-concepts that goes beyond a single-network-service scenario. The presented prototype was implemented using cloud-native containerization technologies (Docker), and

[4]https://mosquitto.org/
[5]https://docker.com/
[6]https://sap.com/products/manufacturing-automation-plant-connectivity.html
[7]https://docs.microsoft.com/en-us/azure/iot-hub/about-iot-hub

was deployed on 5GTANGO's rapid prototyping platform vim-emu. We plan to migrate this deployment to state-of-the-art cluster management technologies (Kubernetes[8]), offering high availability (HA) features. An approach for testing NFV deployments was introduced in [17]. Future work will be on creating test probes for verification and validation of our VNFs and network services to ensure the expected behavior. Further future work will be on the application of network slicing to empower network services on-demand, such as our NS3: the augmented reality (AR) maintenance network service. We have used MQTT as primary message transport protocol, but due to its high degree of acceptance in various sectors we will examine the compatibility to OPC UA more closely in the future.

Acknowledgment

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