

Master Thesis:

Design and Development of a Fog Service
Orchestration Engine for Smart Factories

Master Thesis
from

Markus Paeschke

Supervisor: Prof. Dr.-Ing. Thomas Magedanz
Dr.-Ing. Alexander Willner
Mathias Brito

Markus Paeschke
Trachtenbrodtstr. 32
10409 Berlin

I hereby declare that the following thesis “Design and Development of a Fog Service Orchestration Engine for Smart Factories” has been written only by the undersigned and without any assistance from third parties.

Furthermore, I confirm that no sources have been used in the preparation of this thesis other than those indicated in the thesis itself.

Berlin, February 24, 2017

Markus Paeschke

Acknowledgments

thank your supervisors

thank your colleagues

thank your family and friends

Berlin, February 24, 2017

Abstract

Research Area - write about the research area Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Application Area - write about the application area Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Research Issue - write about the research issue Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Own Approach - write about the own approach Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Scientific Contributions - write about the scientific contributions Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Validation & Outlook - write about the validation and outlook Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Zusammenfassung

Forschungsbereich Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

wrEingrenzungite Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Problemstellung Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Eigener Ansatz Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Wissenschaftlicher Beitrag Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Validierung & Ausblick Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

Contents

| | |
|---|-------------|
| List of Figures | vi |
| List of Tables | vii |
| Quellcodeverzeichnis | viii |
| 1 Introduction | 1 |
| 1.1 Background and Motivation | 1 |
| 1.2 Problem Statement | 2 |
| 1.3 Assumptions and Scope | 2 |
| 1.4 Objectives and Contributions | 2 |
| 1.5 Methodology and Outline | 2 |
| 2 State of the art | 3 |
| 2.1 Internet of Things | 3 |
| 2.1.1 Industry 4.0 and Smart Factories | 4 |
| 2.1.2 Cyber Physical Systems | 6 |
| 2.1.3 Fog Computing | 6 |
| 2.2 Virtualization | 6 |
| 2.2.1 Virtual Machines | 7 |
| 2.2.2 Container Virtualization | 8 |
| 2.2.3 Container Orchestration | 10 |
| 2.2.4 Network Function Virtualization | 10 |
| 2.3 Conclusion | 10 |
| 3 Requirements Analysis | 11 |
| 3.1 Introduction | 11 |
| 3.2 System requirements | 11 |
| 3.3 Technologies | 11 |
| 3.4 Use-Case-Analysis | 11 |
| 3.5 Delineation from existing solutions | 11 |
| 3.6 Conclusion | 11 |
| 4 Design | 12 |
| 4.1 Introduction | 12 |
| 4.2 Development environment | 12 |
| 4.3 Evaluation of existing frameworks | 12 |
| 4.3.1 Docker | 12 |

| | | |
|----------|---|------------|
| 4.3.2 | Docker Swarm | 12 |
| 4.3.3 | Kubernetes | 12 |
| 4.3.4 | Open Baton | 12 |
| 4.3.5 | ETSI MANO | 12 |
| 4.3.6 | TOSCA | 12 |
| 4.4 | Architecture of the system | 12 |
| 4.4.1 | Orchestration layer | 12 |
| 4.4.2 | Constraint layer | 12 |
| 4.4.3 | User interface | 12 |
| 4.5 | Conclusion | 12 |
| 5 | Implementation | 13 |
| 5.1 | Introduction | 13 |
| 5.2 | Project structure | 13 |
| 5.3 | Used external libraries | 13 |
| 5.4 | Custom code | 13 |
| 5.5 | Implementation of the orchestration layer | 13 |
| 5.6 | Implementation of the constraint layer | 13 |
| 5.7 | Implementation of the user interface | 13 |
| 5.8 | Conclusion | 13 |
| 6 | Evaluation | 14 |
| 6.1 | Introduction | 14 |
| 6.2 | Experimental Validation | 14 |
| 6.3 | Performance Evaluation | 14 |
| 6.4 | Observational Validation | 14 |
| 6.5 | Deployments | 14 |
| 6.6 | Code Verification | 14 |
| 6.7 | Comparative Analysis | 14 |
| 6.8 | Conclusion | 14 |
| 7 | Summary and Further Work | 15 |
| 7.1 | Overview | 15 |
| 7.2 | Conclusion and Impact | 15 |
| 7.3 | Outlook | 15 |
| | Acronyms | I |
| | Glossary | II |
| | Bibliography | III |

List of Figures

| | | |
|---|--|---|
| 1 | Horizontal vs. Vertical Integration | 5 |
| 2 | Structure bare-metal virtualization vs. container virtualization | 7 |
| 3 | Docker container structure | 9 |

List of Tables

| | | |
|---|--|---|
| 1 | Design principles of each Industry 4.0 component | 4 |
|---|--|---|

List of Listings

Chapter 1

Introduction

1.1 Background and Motivation

The Internet of Things (IoT) is one of the biggest topic in the recent years. Companies with a focus in that area have an enormous market growth with plenty of new opportunities, use cases, technologies, services and devices. Bain & Company predicts an annual revenue of \$450 billion for companies who selling hardware, software and comprehensive solutions in the IoT context by 2020.[BCJ⁺16] In order to limit the vast area of IoT, more and more standards are defined and subtopics established. The European Research Cluster on the Internet of Things (IERC) devided them into eight categories: Smart Cities, Smart Healthcare, Smart Transport and Smart Industry also known as Industry 4.0 to mention only a few. All of them are well connected, for example a Smart Factory, which is a part of the Smart Industry, can get a delivery from a self driving truck (Smart Transport) which navigates through a Smart City to get to the factory. Such information networks are one of the main goals of IoT. In the Industry 4.0 for example multiple Smart Factories should be interconnect into a distributed and autonomous value chain. Also the automation in a single factory will be increased which helps to have a more flexible and efficient production process. Currently a factory has a high degree of automation, but due to a lack of intelligence and communication between the machines and the underlying system, they can not react to changing requirements or unexpected situations. One solution to achieve that are Cyber-Physical Systems (CPSs). These are virtual systems which are connected with embedded systems to monitor and control physical processes.[Lee08] A normal Cyber Systems (CSs) is passive, means it could not interact with the physical world, with the appearance of CPSs things can communicate so the system has significantly more intelligence in sensors and actuators.[Poo10]

Cloud Computing was one of the prime topic in the recent years. It changed from a monolithic to more distributed multicloud architecture. With the appearance of the Internet of Things (IoT) and related architectures like Fog Computing the cloud moves away from centralized data centers to the edge of the underlying network [1]. Such a network can have thousands of nodes with multiple sensors, machines or smart components connected to them. An "intermediate layer between the IoT environment and the Cloud" [2] enables a lot of new possibilities like pre-computation and storage of gathered data, which reduces traffic and resource overhead in the cloud, it keeps sensitive data on-premise [2] and enables real-time applications to take decisions based on analytics running near the device and a lower latency

[3]. On the other hand there are also a lot of challenges in these highly heterogeneous and hybrid environment. As an example in some scenarios multiple low power devices have to interact with each other, lossy signals and short range radio technologies are widely used and nodes can appear and disappear frequently [3]. Especially the last case is elaborated because the underlying system has to handle that. Furthermore the required applications running on these nodes can be change commonly and have to be deployed and removed in a dynamical way. Virtualization with Virtual Machines (VMs) is a common approach in Cloud systems to provide elasticity of large-scale shared resources[4]. A more lightweight, less resource and time consuming solution is container virtualization. "Furthermore, they are flexible tools for packaging, delivering and orchestration software infrastructure services as well as application"[4]. Orchestration tools like Kubernetes[5], Docker Swarm[6] or CoreOS[7] which deploy, scale and manage containers to clusters of hosts have become established in the last years. Moving this technology over to the IoT area many challenges can be solved. Dynamically deployed applications at the edge of a network can store and preprocesses gather data even if a node have no connection to the cloud because of lossy signals. Traffic can be reduced by only transmitting aggregated data back to the cloud. More often small low-power devices with limited computational power are be used as IoT nodes which also profit rather from lightweight container solutions than from resource consuming VMs. This paper shows the capabilities of container orchestration for the IoT and Smart Factories using the Open Baton framework. Therefor a plugin will be created which can orchestrate Docker containers based on functional and non-functional constraints to fog nodes.

1.2 Problem Statement

1.3 Assumptions and Scope

1.4 Objectives and Contributions

1.5 Methodology and Outline

Chapter 2

State of the art

This chapter will give an overview into the background and concepts of this thesis. In the first section the Internet of Things and related subtopics like Smart Factories and Smart Cities are considered. Cyber Physical Systems, which are important for the development of Smart Factories are also covered in this section. Virtualization in general is the main topic of the second section. First we dive into the area of Virtual Machines, followed by Container Virtualization. Both are related to each other and sharing some basic ideas. Container Orchestration as an own subsection shows some possibilities of Container Virtualization. The last subsection Network Function Virtualization concludes with an introduction into the virtualization of network node functions to create communication services.

2.1 Internet of Things

The IoT has been a subject of great media- and economically growth in the recent years. In the year 2008 the number of devices which are connected to the Internet was higher than the human population.[Eva11, cf.] Cisco Internet Business Solutions Group predicted that the number will grow up to 50 billion in 2020, this equates to around 6 devices per person.[Eva11, cf.] Most of today's interactions are Human-to-Human (H2H) or Human-to-Machine (H2M) communication. The IoT on the other hand aims for the Machine-to-Machine (M2M) communication. This allows every physical device to be interconnected and to communicate with each other. These devices are also called "Smart Devices". Creating a network where all physical objects and people are connected via software is one primary goal of the IoT.[RD15, cf.][KKL13, cf.] When objects are able to capture and monitor their environment, a network can perceive external stimuli and respond to them.[cf. Itu05, p. 40] Therefore a new dimension of information and communication technology will be created, where users have access to everything at any time, everywhere. In addition to smart devices, subcategories are also emerging from the IoT which, in addition to the physical devices, also describe technologies such as protocols and infrastructures. The "Smart Home" has been a prominent topic in media and business for many years. Smart City or Industrie 4.0 are also becoming established and are increasingly popular. But the Internet started with the appearance of bar codes and Radio Frequency Identification (RFID) chips.[KKL13, cf.] The second step, which is more or less the current situation, sensors, physical devices, technical devices, data and software are connected to each other.[KKL13, cf.] This was achieved, in particular, by

cloud computing, which provides the highly efficient memory and computing power that is indispensable for such networks.[RD15, cf.] The next step could be a "Cognitive Internet of Things", which enables easier object and data reuse across application areas, for example through interoperable solutions, high-speed Internet connections and a semantic information distribution.[KKL13, cf.] Just as the omnipresent information processing in everyday life, also known as "Ubiquitous Computing", which was first mentioned in the "The Computer for the 21st Century"[Wei91, cf.] by Marks Weiser, it will take some time until it is ubiquitous.

2.1.1 Industry 4.0 and Smart Factories

The industry as an changing environment is currently in the state of the so called "fourth industrial revolution". The first industrial revolution was driven by steam powered machines. Mass production and division of labor was the primary improvement of the second industrial revolution, whereas the third revolution was characterized by using electronics and the integration of Information Technology (IT) into manufacturing processes.[cf. LPS16, p. 1] In the recent years the size, cost and power consumption of chipsets are reduced which made it possible to embed sensors into devices and machines much easier and cheaper.[cf. BHSW16, p. 1] The Industry 4.0 is the fourth step in this evolution and was first mentioned with the German term "Industrie 4.0" at the Hannover Fair in 2011.[cf. LPS16, p. 1] "Industrie 4.0 is a collective term for technologies and concepts of value chain organization." [cf. HPO15, p. 11]

Significantly higher productivity, efficiency, and self-managing production processes where everything from machines up to goods can communicate and cooperate with each other directly are the visions of the Industry 4.0.[Lyd16, cf.] It also aims for an intelligent connection between different companies and units. Autonomous production and logistics processes creating a real-time lean manufacturing ecosystem that is more efficient and flexible.[Lyd16, cf.] "This will facilitate smart value-creation chains that include all of the life-cycle phases of the product from the initial product idea, development, production, use, and maintenance to recycling." [Lyd16] At the end, the system can use customer wishes in every step in the process to be flexible and responsive.[Lyd16, cf.]

| | Cyber-Physical Systems | Internet of Things | Internet of Services | Smart Factory |
|----------------------|------------------------|--------------------|----------------------|---------------|
| Interoperability | X | X | X | X |
| Virtualization | X | - | - | X |
| Decentralization | X | - | - | X |
| Real-Time Capability | - | - | - | X |
| Service Orientation | - | - | X | - |
| Modularity | - | - | X | - |

Table 1: Design principles of each Industry 4.0 component.[cf. HPO15, p. 11]

Table 1 shows the six design principles which can be from the Industrie 4.0 components. They can help companies to identify and implement Industry 4.0 scenarios.[cf. HPO15, p. 11]

1. *Interoperability* CPS of various manufacturers are connected with each other. Standards will be the key success factor in this area.[cf. HPO15, p. 11]

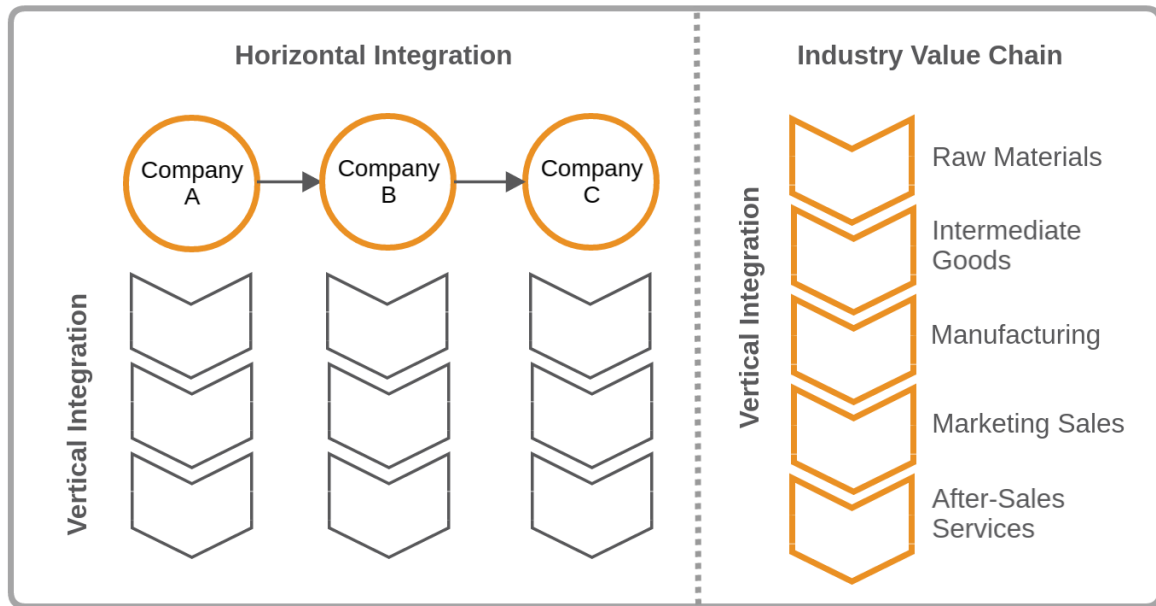


Figure 1: Horizontal vs. Vertical Integration. Adapted from: [Jur13]

2. *Virtualization* CPS are able to monitor physical processes via sensors. The resulting data is linked to virtual plant and simulation models. These models are virtual copies of physical world entities.[cf. HPO15, p. 11]
3. *Decentralization* CPS are able to make decisions on their own, for example when RFID chips send the necessary working steps to the machine. Only in cases of failure the systems delegate task to a higher level.[cf. HPO15, p. 11]
4. *Real-Time Capability* Data has to be collected and analyzed in real time and the status of the plant is permanently tracked and analyzed. This enables the CPS to react to a failure of a machine and can reroute the products to another machine.[cf. HPO15, p. 11]
5. *Service Orientation* CPS are available over the Internet of Services (IoS) and can be offered both internally and across company borders to different participants. The manufacturing process can be composed based on specific customer requirements.[cf. HPO15, p. 11]
6. *Modularity* The system is able to be adjusted in case of seasonal fluctuations or changed product characteristics, by replacing or expanding individual modules.[cf. HPO15, p. 11]

Another important aspect of Industry 4.0 is the implementation of process automation with the focused on three distinct aspects. Starting with the vertical integration, which contains the connection and communication of subsystems within the factory enables flexible and adaptable manufacturing systems.[cf. Vbw14, p. 7 ff.] The horizontal integration, as the second aspect, enables technical processes to be integrated in cross-company business processes and to be synchronized in real time through multiple participants to optimize value chain outputs.[cf. Vbw14, p. 7 ff.] Finally end-to-end engineering, planning, and process control for each step in the production process.[Lyd16, cf.]

Figure 1 illustrates this concept. The left side shows the whole production process over company boundaries on the horizontal scale, as well as the industry value chain on the vertical scale which is specific for each company. On the right side there is an exemplary industry value chain which starts with the raw materials and ends with the sale of the product to illustrates an more specific example of the vertical integration.

guter abschluss -> moving production steps to each machine -> modular, without core system, locally in the modules -> communication path growth shorter -> self organisation -> decentralized

as well as highly flexible, individualized and resource friendly mass production

2.1.2 Cyber Physical Systems

As we already now, in smart factories every physical device is connected to each other. Everything can be captured and monitored in each step of a production process. With CPSs every physical entity has a digital representation in the virtual system.[cf. Poo10, p. 1363] Before a CS was passive, which means it has no communication between the physical and the virtual world.[cf. Poo10, p. 1364] While new technologies in the physical world, like new materials, hardware and energy, are developed, the technologies in the virtual worlds are also being improved, for example through the use of new protocols, networking, storage and computing technologies.[cf. Poo10, p. 1364] This adds more intelligence in such systems, as well as a much more flexible and modular structure. A CPS can organize production automatically and autonomously, which eliminate the need of having a central process control.[? , cf.] Thereby the system can handle lossy signals and short range radio technologies, which are widely used in such a context.[YMSG⁺14, cf.] write more

2.1.3 Fog Computing

2.2 Virtualization

According to the National Institute of Standards and Technology (NIST) the definition of virtualization is: "Virtualization is the simulation of the software and/or hardware upon which other software runs. This simulated environment is called a virtual machine (VM)."[SSH11]. This means a Virtual Machine (VM), also referred as guest system, can be executed in a real system, which is referred as host system. A VM has its own Operating System (OS) which is completely isolated from the other VMs and the host system.[cf. CMF⁺16, p. 2] Basically there are two types of virtualization: Process virtualization where the virtualizing software also known as Virtual Machine Monitor (VMM) is executed by the host OS and only an application will be executed inside the guest OS and on the other side there is the the system virtualization where the whole OS as well as the application are running inside the virtualizing software. Figure 2 illustrate both concepts. Examples for process virtualization could be the Java Virtual Machine (JVM)¹, the .Net framework² or Docker³, where VMWare⁴, Oracle

¹<https://www.java.com>

²<https://www.microsoft.com/net>

³<https://www.docker.com>

⁴<http://www.vmware.com>

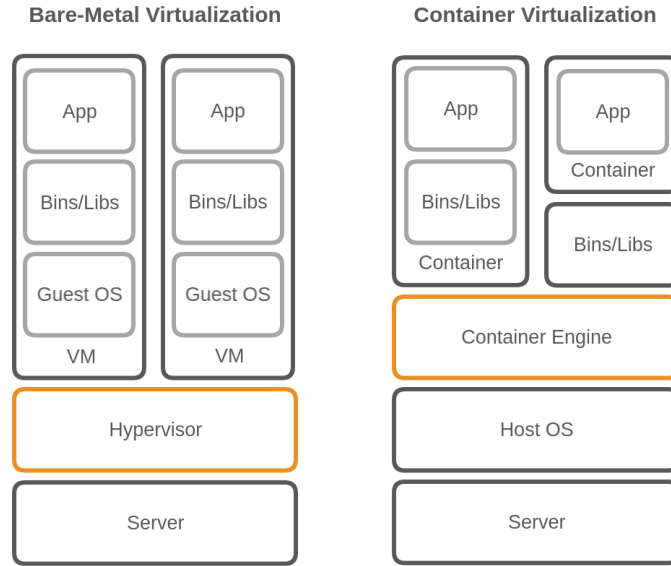


Figure 2: Structure bare-metal virtualization vs. container virtualization. Adapted from: [Gal15, p. 2]

Virtual Box⁵, XEN⁶ or Microsoft Hyper-V⁷ are only some examples for system virtualization. The benefits of all virtualization techniques are the rapid provisioning of resources which could be Random Access Memory (RAM), disk storage, computation power or network bandwidth. Beside that, no human interaction is necessary during the provisioning process. Elasticity which scales a system in a cost-efficient manner in both directions, up and down. Customer as well as the provider profit from such a system. Security based on the isolation of the VMs is another huge benefit. Different processes can not interfere with each other and the data of a single user can not be accessed by other users of the same hardware. A challenge despite all the mentioned benefits is the performance. Running VMs increases the overhead and reduces the overall performance of a system. Therefore the specific use case have to consider these behavior.

2.2.1 Virtual Machines

VMs are the core virtualization mechanism in cloud computing. There are also two different designs for hardware virtualization. The first and more popular type for cloud computing is the *bare-metal virtualization*. It needs only a basic OS to schedule VMs. The hypervisor runs directly on the hardware of the machine without any host OS in between. This is more efficient, but requires special device drivers to be executed. The other type is the *hosted virtualization*. Unlike the first type the VMM run as a host OS process and the VMs as a process supported by the VMM. No special drivers are needed for these type of virtualization, but by comparison the overhead is much bigger. For both types, the performance limitation remains. Each VM need a full guest OS image in addition to binaries and libraries which are

⁵<https://www.virtualbox.org>

⁶<https://www.xenproject.org>

⁷<https://www.microsoft.com/de-de/cloud-platform/server-virtualization>

necessary for the application to be executed.[cf. PL15, p. 381] If only a single application, which only needs a few binaries and libraries, is needed to be virtualized, VMs are too bloated.

2.2.2 Container Virtualization

Container virtualization which is also known as Operating System-level virtualization, is the second virtualization mechanism. It based on fast and lightweight process virtualization to encapsulate an entire application with its dependencies into a ready-to-deploy virtual container.[cf. TRA15, p. 72] Such a container can be executed on the host OS which allows an application to run as a sandboxed user-space instance.[cf. AHA⁺16, p. 1] All containers share a single OS kernel, so the isolation supposed to be weaker compared to hypervisor based virtualization.[cf. CMF⁺16, p. 2] Compared to VMs, the number of containers on the same physical host can be much higher, because the overhead of a full OS virtualization is eliminated.[cf. CMF⁺16, p. 2]

Linux Containers

When we talk about container virtualization nowadays, Docker have to become one of the most famous tools out there. It based on Linux Containers (LXC)⁸ a technology which uses kernel mechanisms like *namespaces* or *cgroups* to isolate processes on a shared OS.[cf. PL15, p. 381] Namespaces for example are used to isolate groups of processes whereas cgroups are used to manage and limit resources access just like restricting the memory, disc space or Central Processing Unit (CPU) usage.[cf. PL15, p. 381] "The goal of LXC is to create an environment as close as possible to a standard Linux installation but without the need for a separate kernel." [TRA15, p. 72] There are several other container virtualization tools out there like OpenVZ⁹ or Linux-VServer¹⁰. In contrast to them, an advantage of LXC is that it runs on an unmodified Linux kernel. This means that LXC can be executed in most of the popular Linux distributions these days.

Docker

As mentioned before, Docker based on LXC. This allows the Docker Engine to build, deploy and run containers in an easy and customizable way. Similar to VMs, containers are executed from images. A mayor benefit of Docker is the fact, that Docker images can be combined like build blocks. Each image can build on top of another. Figure 3 illustrates the concept for the image of the pretty famous Django¹¹ web framework. In that case, the Django image, which is the resulting image, based on the Python 3.4 image which again based on the Debian Jessie image. All of them are read-only, but Docker adds a writeable layer, also known as *container layer*, on top of the images as soon as the container will be created. File system operations such as creating new files, modifying or deleting existing files are written directly to these layer.[Docb, cf.] The other images don't get involved. These chaining mechanism of images allows Docker to ease the use of dependencies and administrative overhead.

⁸<https://linuxcontainers.org/>

⁹https://openvz.org/Main_Page

¹⁰<http://www.linux-vserver.org>

¹¹<https://www.djangoproject.com/>

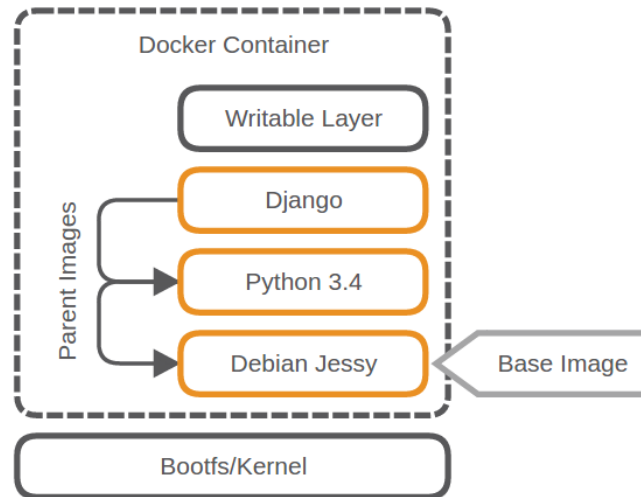


Figure 3: Docker container structure.

Beside that, Docker is splitted up in several components, such as the Docker Engine, the Docker Registries and Docker Compose to mention only a few. The Docker Engine is a client-server application which can be distinguished by the Docker client, a Representational State Transfer (REST) Application Programming Interface (API) and the Docker server. Latter is a daemon process which "creates and manages Docker objects, such as images, containers, networks, and data volumes"[Doca]. The client is a Command Line Interface (CLI), which interact via a REST API with the daemon.[Doca, cf.]

Another component, the Docker Registry, is basically a library of Docker images. They can be public or private available, as well as on the same machine like the Docker daemon or an external server.[Doca, cf.] The most popular one it the official Docker Hub¹². There is also an Docker Store¹³, where customers can buy and sell trusted and enterprise ready containers and plugins. With the Docker client it is pretty easy to *search* for new containers and to *pull* containers from or *push* containers to a specific repository.

With Docker Compose multiple Docker Containers can be executed as a single application. Therefore YAML compose file will be used to configure and combine the services. For example the already mentioned Django image can be executed and linked together with a MongoDB¹⁴ images. The main benefit is the ease of configure dependencies between several containers and configuration steps. These concept is similar to deployment tools like Vagrant¹⁵, Ansible¹⁶ or Puppet¹⁷.

A major benefit of Docker is that the execution environment of an application is completely the same on a local machine as on the production environment.[cf. Gal15, p. 2] There is no need to do things differently when switching from a development environment like a local machine, to a production environment like a server.[cf. Gal15, p. 2]

¹²<https://hub.docker.com>

¹³<https://store.docker.com>

¹⁴<https://www.mongodb.com>

¹⁵<https://www.vagrantup.com>

¹⁶<https://www.ansible.com>

¹⁷<https://puppet.com>

2.2.3 Container Orchestration

Kubernetes

Docker Swarm

2.2.4 Network Function Virtualization

2.3 Conclusion

Chapter 3

Requirements Analysis

3.1 Introduction

3.2 System requirements

3.3 Technologies

3.4 Use-Case-Analysis

3.5 Delineation from existing solutions

3.6 Conclusion

Chapter 4

Design

4.1 Introduction

4.2 Development environment

4.3 Evaluation of existing frameworks

4.3.1 Docker

4.3.2 Docker Swarm

4.3.3 Kubernetes

4.3.4 Open Baton

4.3.5 ETSI MANO

4.3.6 TOSCA

4.4 Architecture of the system

4.4.1 Orchestration layer

4.4.2 Constraint layer

4.4.3 User interface

4.5 Conclusion

Chapter 5

Implementation

5.1 Introduction

5.2 Project structure

5.3 Used external libraries

5.4 Custom code

5.5 Implementation of the orchestration layer

5.6 Implementation of the constraint layer

5.7 Implementation of the user interface

5.8 Conclusion

Chapter 6

Evaluation

6.1 Introduction

6.2 Experimental Validation

6.3 Performance Evaluation

6.4 Observational Validation

6.5 Deployments

6.6 Code Verification

6.7 Comparative Analysis

6.8 Conclusion

Chapter 7

Summary and Further Work

7.1 Overview

7.2 Conclusion and Impact

7.3 Outlook

Acronyms

| | |
|-------------|---|
| API | Application Programming Interface |
| CLI | Command Line Interface |
| CPU | Central Processing Unit |
| CPS | Cyber-Physical System |
| CS | Cyber System |
| H2H | Human-to-Human |
| H2M | Human-to-Machine |
| IERC | European Research Cluster on the Internet of Things |
| IoS | Internet of Services |
| IoT | Internet of Things |
| IT | Information Technology |
| JVM | Java Virtual Machine |
| LXC | Linux Containers |
| M2M | Machine-to-Machine |
| NIST | National Institute of Standards and Technology |
| OS | Operating System |
| RAM | Random Access Memory |
| REST | Representational State Transfer |
| RFID | Radio Frequency Identification |
| VM | Virtual Machine |
| VMM | Virtual Machine Monitor |

Glossary

Algorithmus a

Chiffrierung a

Dechiffrierung a

Bibliography

- [AHA⁺16] ANDERSON, J. ; HU, H. ; AGARWAL, U. ; LOWERY, C. ; LI, H. ; APON, A.: Performance considerations of network functions virtualization using containers. In: *2016 International Conference on Computing, Networking and Communications (ICNC)*, 2016, S. 1–7
- [BCJ⁺16] BOSCHE, A. ; CRAWFORD, D. ; JACKSON, D. ; SCHALLEHN, M. ; SMITH, P.: *How Providers Can Succeed in the Internet of Things*. <http://bain.com/publications/articles/how-providers-can-succeed-in-the-internet-of-things.aspx>. Version: Aug 2016. – Accessed: 2017-02-20
- [BHSW16] BRITO, M. S. D. ; HOQUE, S. ; STEINKE, R. ; WILLNER, A.: Towards Programmable Fog Nodes in Smart Factories. In: *2016 IEEE 1st International Workshops on Foundations and Applications of Self* Systems (FAS*W)*, 2016, S. 236–241
- [CMF⁺16] CELESTI, A. ; MULFARI, D. ; FAZIO, M. ; VILLARI, M. ; PULIAFITO, A.: Exploring Container Virtualization in IoT Clouds. In: *2016 IEEE International Conference on Smart Computing (SMARTCOMP)*, 2016, S. 1–6
- [Doca] *Docker Overview - Docker*. <https://docs.docker.com/engine/understanding-docker/>, . – Accessed: 2017-02-24
- [Docb] *Understand images, containers, and storage drivers - Docker*. <https://docs.docker.com/engine/userguide/storagedriver/imagesandcontainers/>, . – Accessed: 2017-02-24
- [Eva11] EVANS, D.: The Internet of Things: How the Next Evolution of the Internet Is Changing Everything / Cisco Internet Business Solutions Group (IBSG). Version: April 2011. http://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf. 2011. – Forschungsbericht. – Accessed: 2017-02-12
- [Gal15] GALLAGHER, S.: *Mastering Docker*. Packt Publishing Ltd., 2015. – ISBN 978–1–78528–703–9
- [HPO15] HERMANN, M. ; PENTEK, T. ; OTTO, B.: Design Principles for Industrie 4.0 Scenarios: A Literature Review / Technische Universität Dortmund - Fakultät Maschinenbau. Version: Jan 2015. <http://www.thiagobranquinho.com/wp-content/uploads/2016/11/>

- Design-Principles-for-Industrie-4_0-Scenarios.pdf. 2015. – Forschungsbericht. – Accessed: 2017-02-12
- [IER11] IERC - EUROPEAN RESEARCH CLUSTER ON THE INTERNET OF THINGS: Internet of Things - Pan European Research and Innovation Vision. Version: Oktober 2011. http://www.theinternetofthings.eu/sites/default/files/Rob%20van%20Kranenburg/IERC_IoT-Pan%20European%20Research%20and%20Innovation%20Vision_2011.pdf; letzter Zugriff: 27.06.2016, 14:07Uhr. 2011. – Forschungsbericht
- [Itu05] INTERNATIONAL TELECOMMUNICATION UNION: ITU Internet Reports: The Internet of Things. Version: November 2005. <https://www.itu.int/net/ws/tunis/newsroom/stats/The-Internet-of-Things-2005.pdf>. 2005. – Forschungsbericht. – Accessed: 2017-02-12
- [Jur13] JUREVICIUS, O.: *Vertical Integration*. <https://www.strategicmanagementinsight.com/topics/vertical-integration.html>. Version: April 2013. – Accessed: 2017-02-13
- [KKL13] KRAMP, T. ; KRANENBURG, R. van ; LANGE, S.: Introduction to the Internet of Things. In: *Enabling Things to Talk* Bd. 1, Springer-Verlag Berlin Heidelberg, 2013. – ISBN 978–3–642–40402–3, S. 1–10
- [Lee08] LEE, E. A.: Cyber Physical Systems: Design Challenges. In: *2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)*, 2008. – ISSN 1555–0885, S. 363–369
- [LPS16] LOM, M. ; PRIBYL, O. ; SVITEK, M.: Industry 4.0 as a part of smart cities. In: *2016 Smart Cities Symposium Prague (SCSP)*, 2016, S. 1–6
- [Lyd16] LYDON, B.: Industry 4.0: Intelligent and flexible production. In: *InTech Magazine* (2016), May-June. <https://www.isa.org/intech/20160601/>. – Accessed: 2017-02-13
- [PL15] PAHL, C. ; LEE, B.: Containers and Clusters for Edge Cloud Architectures – A Technology Review. In: *2015 3rd International Conference on Future Internet of Things and Cloud*, 2015, S. 379–386
- [Poo10] POOVENDRAN, R.: Cyber Physical Systems: Close Encounters Between Two Parallel Worlds. In: *Proceedings of the IEEE* 98 (2010), Aug, Nr. 8, S. 1363–1366. <http://dx.doi.org/10.1109/JPROC.2010.2050377>. – DOI 10.1109/JPROC.2010.2050377. – ISSN 0018–9219
- [RD15] RUI, J. ; DANPENG, S.: Architecture Design of the Internet of Things Based on Cloud Computing. In: *2015 Seventh International Conference on Measuring Technology and Mechatronics Automation*, 2015. – ISSN 2157–1473, S. 206–209
- [SPF⁺07] SOLTESZ, S. ; PÖTZL, H. ; FIUCZYNSKI, M. E. ; BAVIER, A. ; PETERSON, L.: Container-based Operating System Virtualization: A Scalable, High-performance Alternative to Hypervisors. In: *Proceedings of the 2Nd ACM SIGOPS/EuroSys European Conference on Computer Systems 2007*. New York, NY, USA : ACM, 2007 (EuroSys '07). – ISBN 978–1–59593–636–3, 275–287

- [SSH11] SCARFONE, K. ; SOUPPAYA, M. ; HOFFMAN, P.: Guide to Security for Full Virtualization Technologies / National Institute of Standards and Technology. Version: Jan 2011. <http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-125.pdf>. 2011. – Forschungsbericht. – Accessed: 2017-02-19
- [TRA15] TOSATTO, A. ; RUIU, P. ; ATTANASIO, A.: Container-Based Orchestration in Cloud: State of the Art and Challenges. In: *2015 Ninth International Conference on Complex, Intelligent, and Software Intensive Systems*, 2015, S. 70–75
- [Vbw14] VBW VEREINIGUNG DER BAYERISCHEN WIRTSCHAFT E. V.: Dienstleistungspotenziale im Rahmen von Industrie 4.0. Version: Mar 2014. <http://www.forschungsnetzwerk.at/downloadpub/dienstleistungspotenziale-industrie-4.0-mar-2014.pdf>. 2014. – Forschungsbericht. – Accessed: 2017-02-12
- [Wei91] WEISER, M.: *The Computer for the 21st Century*. <http://www.ubiq.com/hypertext/weiser/SciAmDraft3.html>. Version: September 1991. – Accessed: 2017-02-12
- [YMSG⁺14] YANNUZZI, M. ; MILITO, R. ; SERRAL-GRACIÀ, R. ; MONTERO, D. ; NEMIROVSKY, M.: Key ingredients in an IoT recipe: Fog Computing, Cloud computing, and more Fog Computing. In: *2014 IEEE 19th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, 2014. – ISSN 2378–4865, S. 325–329

