Towards a Software Architecture for Near Real-time Applications of IoT

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Abstract: The number of Internet of Things (IoT) devices increases and will become an ever important source of information made available through their sensors. As a result, devices form denser networks producing a huge variety and volume of data. If intercommunication and interaction between many decentralized resources are not considered as primary objective by vendors, networking distributed IoT devices will be complicated due to their heterogeneity. Thus, mastering the challenge of collecting and processing data with low-latency is a difficult task. In this paper, we present a practical and easy to employ reference software architecture for fog computing application scenarios, enabling the communication between a multitude of devices which require an efficient and robust real-time system. As proof, we conduct a practical demonstration—a three-dimensional mouse is constructed, called the Cube-It, to control a six-joint robot (i.e., the UR10). The findings of this work are expected to aid researchers studying the integration of heterogeneous IoT devices within fog computing environments comprising many sensors and actuators.

1 INTRODUCTION

Billions of devices will be connected to the internet until 2020 (Evans, 2011), forming a massive machine-to-machine network between smart devices, sensors, and actuators. The amount of data that is created and send over the network vastly increases as well. As IoT is becoming more prominent and the number of devices increases, they will become an ever important source of information as they are generating data through their sensors. From these, various kinds of decisions can be made by leveraging the interrelation of multiple sensor information. More and more traffic in a network will be generated and becomes a burden for low-bandwidth and high-latency networks. Therefore, applications of IoT must cope with the vast amount of data and react and respond in near real-time. Low-latency is an essential attribute for IoT applications (Bonomi et al., 2014).

Former computing models such as the Cloud are not sufficient for **latency-sensitive applications** and **distributed computing for a considerable number of heterogeneous devices, sensors, and actuators** (Bonomi et al., 2012). So far, cloud-based solutions are inadequate. As the physical distance between the user and cloud increases, transmission latency and response time increases as well. For the real-time requirement, vast amounts of data in low-bandwidth networks must be processed and transmitted. Concerning the distributed computing requirement, a distributed system of devices communicating via central nodes or directly with each other must be established ad-hoc or permanently for facilitating the interoperability among services and devices, but also scalability.

The next logical step is to push the cloud services to the edge of the network of the devices to gather the actual data close to their respective origins. This is known as **fog computing**. Data processing is performed during its collection, enabling local decision making at these devices instead of a physically distant cloud server. This significantly reduces the amount of data that is being sent through the network and reduces the bandwidth needed. We propose a fog computing architecture for service-oriented IoT applications with the following objectives:

- **Separation of Concerns (SoC):** The connection of new sensors and actuators is realized through a data-driven approach leaving most of the service logic unaffected when adding, changing or removing hardware.
- **Distribution:** Handling distributed computing among a vast number of devices through an abstract message bus that provides means for data exchange between services. Furthermore, services are deployed near devices performing the

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actual task to facilitate the near real-time requirement.

- **Availability and Scalability:** This objective indicates that core parts of the architecture and services of IoT applications are resilient to node failures. This is achieved by the provision of redundant services and constant monitoring to recover degraded services automatically.

1.1 Related Work

Bonomi et al. (Bonomi et al., 2014) expound a software architecture for fog computing highlighting key objectives such as low and predictable latency, geographically distributed devices and interplay with the cloud. The main constituents of the architecture are the *fog abstraction layer* (exposes a uniform interface for management and control by providing APIs for monitoring, provisioning and controlling physical resources), *orchestration layer* (distributed, policy-based life-cycle management of services, also including a messaging bus), and the *data APIs layer* (applications use these to leverage the fog platform, e.g., storing and getting data). We, however, use the messaging bus not only to transmit control messages for service orchestration and resource management as in (Bonomi et al., 2014) but also to carry application-specific data as well as sensor and actuator data.

Lisa 2.0 (Negash et al., 2016) is a low-level IoT framework based directly on a real-time enabled micro kernel RIOT. Therefore, the framework has a low footprint, real-time guarantees, and low latency. In contrast to our software architecture, messaging technology and service distribution is custom built and is not integrating well with existing middle-wares.

A framework for home automation focusing on privacy is ParaDrop (Willis et al., 2014; Liu et al., 2016). This framework can be deployed, for example, on WiFi access points due to its small footprint. Thus, reducing the latency by bringing the middleware closer to the data. The framework can be hosted inside Docker containers, similar to our approach. However, it is not clear whether the framework can be extended with other messaging protocols as with our architecture.

DIAT (Distributed Internet-like Architecture for Things) (Sarkar et al., 2015) is an IoT middleware, which focuses on context adaptivity and privacy. The architecture of DIAT comprises the following three layers, which form a stack, called the IoT daemon. The *virtual object layer* which is closest to the physical world and provides a virtual representation of sensors. The *composite virtual object layer* composes multiple virtual object layers and allows distribution, and enables discovery and matching of virtual objects. Lastly, the *service layer* which is closest to the end-user and provides high-level control of all devices. Even though this layered architecture is designed for interoperability, this requirement is only ensured among the three layers (the IoT daemon has to run on every IoT object). Compared to our architecture, we utilize a data-driven approach for the representation of sensors and actuators of the physical world. The outputs and inputs are modelled using a model language, decoupled from the software components. This facilitates interoperability and integration between applications within our architecture and completely different IoT applications.

1.2 Structure

Our paper is structured as follows. In Section 2, we propose a novel concept of a low-latency software reference architecture facilitating near real-time applications for the fog. As proof, we demonstrate the implementation and usefulness of our architecture with one robotic demonstrator (Section 3)—a three-dimensional mouse for real-time control of a robotic arm. Our case study shows that we can implement such an approach using our reference architecture. Finally, conclusions are offered in Section 4, were we are also giving an outlook on what is left for future work.

2 REAL-TIME SOFTWARE REFERENCE ARCHITECTURE FOR IOT APPLICATIONS

The system's primary task is to route data between multiple different IoT devices in a robust, efficient manner in near real-time, allowing further data processing in between the routes. Fog computing serves as an optimal choice when requiring distribution, scalability and real-time (Bonomi et al., 2014; Al-Fuqaha et al., 2015). Such fog-based systems are characterized by their operational independence, physical distribution, number and type of devices. Thus, the requirements of the system are manifold. Considering the challenges of IoT as described by Al-Fuqaha et al. (Al-Fuqaha et al., 2015), we adopt several of these and aligning them with the goals established in the introduction (Section 1) to implement our service infrastructure efficiently, including (i) **Fault-tolerance**: Eliminating the single point of failure (SPF)—if one service fails, the system must still operate appropriately according to the task;

(ii) **Scalability**: Functionality on devices must be deployed automatically when the network load reaches a critical limit; (iii) **Performance**: Achieving minimal lag between sensor readings, estimation, processing and finally control; (iv) **Updatability**: Ensuring on-the-fly updates leads to a more robust, reliable software.

2.1 Architectural Components

This section introduces and discusses the components and technologies that are used as the building blocks for the proposed software architecture explained in Section 2.2.

OSGi. The OSGi Alliance specifies the OSGi standard for the modularization of Java applications in a service-oriented manner as the Java platform itself provides limited support for packaging and deploying Java-based applications.[1] As a result, to resolve this issue, the OSGi framework uses the notion of *bundles* which define a unit of modularization.

A bundle is a Java ARchive (JAR) file which contains various resources and Java class files to provide functionality and can also embed additional JAR files. Within the OSGi framework bundles provide a standard to share and deploy components as bundles. The visibility of bundles can be controled by hiding them from other bundles or make them visible only for a specific group. Moreover, the framework provides mechanisms to define constraints to match imports to exports.

Docker. Docker[2] is an open source project based on Linux containers that enable an isolated, self-contained unit for development, deployment, and execution of programs. The usage of kernel features enables the creation of self-contained environments for applications that can be built, shared, deployed and executed on-demand. Everything that is needed to run the software is part of the container.

Kubernetes. One of the central points in fog computing scenarios is the deployment of workflows close to computing, storage and networking devices and devices that generate data. This concept enhances privacy, minimizes lags and delays. Furthermore, data that needs to be transferred to cloud endpoints is minimized. In Kubernetes[3], a cluster represents a collection of hosts and their resources, including computing, storage and networking to run workloads. Hosts are either physical or virtual machines that run workloads packaged as pods.Bundles are packaged in containers, which in turn are then deployed with Kubernetes at the, possible heterogeneous, edge devices.

MQTT. Message Queuing Telemetry Transport (MQTT) (ISO/IEC, 2016) is a lightweight and widely used messaging protocol on top of TCP/IP and is used for machine-to-machine (M2M) communication with built-in support of quality of service (QoS). It is optimal for real-time communication between embedded devices in low-bandwidth environments with its binary format containing only 2 bytes of header information.

MQTT implements the publisher/subscriber message pattern using a broker. Each client connects to a broker and can subscribe to topics and publish messages through the broker. The broker is responsible for delivering messages to the subscribed clients while it receives all messages from the clients and sends them to all clients subscribed to a specific topic. A topic is a hierarchically structured string where one or more levels can be defined when a forward slash separates them. The most popular open source MQTT broker implementation is Mosquitto (Light, 2017).

2.2 System Description

A high-level description of the proposed architecture is shown in Figure 1. The core of our infrastructure is a service-based middleware which provides efficient support for service acquisition, discovery, and deployment on edge nodes. Each *service* (that is, an OSGi bundle) is developed and deployed separately. Each bundle runs independently with its own set of functionality, communicates through the central message bus and works together with other services to carry out specific tasks. The logic of the workflow can be separated into different services and distributed accordingly in the edge network. This degree of modularity is realized using OSGi and MQTT (refer to Section 2.1).

The services are deployed on different hosts and interact with each other through the message bus. Services can request other services even on different hosts (dependency). The dynamic service injection and update into the system are supported without the need to restart the whole application (see Section 2.3). Nevertheless, services are bound to their current scope in the running JVM. To allow distribution across several devices in the network edge the deployment and scaling of services is performed

[1] OSGi Core Release 5, http://www.osgi.org

[2] https://www.docker.com/

[3] https://kubernetes.io/

through the *orchestration layer* (see Figure 1 and Section 2.5).

The *message bus* (see Section 2.4) is a cluster of *message brokers*. A message broker consumes messages from producers and publishes these to its consumers. Multiple brokers form a cluster. The cluster is accessed through a *load balancer* to give a single point of entry and is managed by the orchestration layer as well (see Section 2.5).

Furthermore, the orchestration layer's task is to monitor the health of each service, the load balancer and message broker cluster based on several QoS metrics. For example, in case the load balancer should fail to be available under critical network load, the orchestration layer will be responsible for the provision of redundant load balancers.

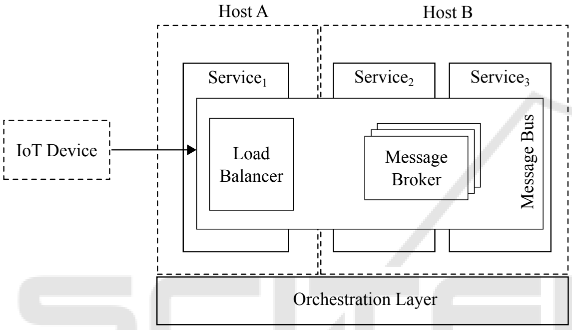


Figure 1: High-level system infrastructure for applications of IoT. Services are deployed on different hosts (here *Host A* and *Host B*). The services interact with each other through the message bus. The message bus comprises a cluster of message brokers where the cluster is accessed through a load balancer. Services can request other services (dependencies) deployed on different hosts. The orchestration layer manages the deployment of the services and message bus components. Additionally, it is ensuring its scalability under load. Devices which are not able to host services on themselves due to limited processing power, can access the functionality of other services via the message bus and also.

Data processing takes places on edge nodes at the edge computing layer, thus, minimising latency and enabling shorter response-times. This improves the overall application performance when computing can be done locally next to edge devices where the data is generated, and actions are executed. To allow this kind of distributed processing the services communicate over the message bus with each other. This abstraction layer allows the implementation of various message queue technologies.

Regarding the representation of sensors and actuators, we utilize a data-driven approach. Therefore, a platform-agnostic language is used, which allows to describe the inputs and outputs of the hardware. At the same time, the model allows the generation of source code for a variety of programming languages which can be used to serialize and deserialize the hardware's data. For example, the data format for the information exchange of sensor and actuator data is achieved using a message format such as *Cap'n Proto*, *Google Protobuf* or *Apache Avro*.

communicate with actuators by transmitting the changes back or read sensor values directly in the service—all specified in advance by the model.

2.3 Dynamic Services

We use *concierge* on edge nodes as a lightweight version of the OSGi framework, which currently implements the OSGi Core Specification R5 standard. This small-footprint implementation is optimized for mobile and embedded devices (Rellermeyer and Alonso, 2007), which makes this implementation variant of OSGi preferably in IoT environments. The key features of OSGi, including modularity through the bundle concept, runtime dynamics for managing components at runtime and the possibility of inter-component communication through services.

OSGi enables on-the-fly updates of the services through its dynamic services without restarting the system. Services are going through a specific lifecycle that is depicted in Figure 2, and closely correspond the OSGi bundle lifecycle. The dynamic nature of the

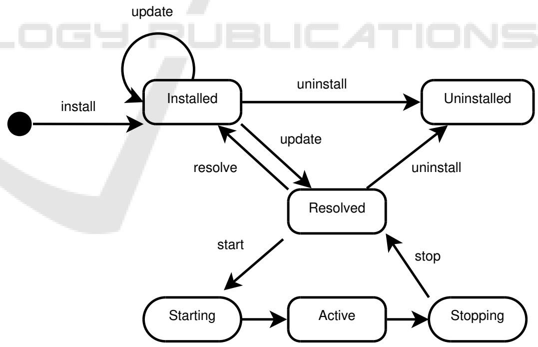


Figure 2: Bundle lifecycle.

OSGi platform transitions a bundle through different states in their lifecycle. The lifecycle shows how a bundle transits from one state to another. The system moves a bundle dynamically at runtime between the *installed*, *resolved*, *active*, and *uninstalled* state depending on their current constraints. As a result, for instance, the starting order of the services are not important even if they depend on each other or rely on specific functionality. Since the state of each service is submitted to the interested partner component, it can wait until the corresponding service becomes available.

Services are looked up via the *OSGi Service Registry* whereas the *Service Provider* is used to publish services. Thus, OSGi follows the principles of a service-oriented architecture (McAffer et al., 2010). As mentioned in the introduction of this section, services are limited to the JVM on which they are running. To locate services that are distributed on other devices, we perform deployments managed by Kubernetes (see Section 2.5) allowing the automatic orchestration of services. That enables services to define dependencies that are deployed on other hosts. This kind of service associations enables high reliability of the entire system compared to statically wired dependencies which make it hard to change functionality at runtime without shutting down the system.

2.4 Message Bus

The message bus is a vital aspect of a distributed processing system. Each device and service interacts with each other over a network. In order to handle the coordination of each participant in the system, the communication is carried out by sending messages over a bus system. This allows an event source to send many fine-grained events to several listeners. Regarding OSGi, the *Event Admin Service* is provided to allow the realisation of an *Event Broker* pattern. The Event Admin offers message-based functionality through publish/subscribe feature.

Different *message bus variants* can be implemented due to the fact that the whole messaging queue layer is completely abstracted away via the *OSGi Event Admin Service*. As a result, there exists virtually no limitation for utilising any message queue technology. For instance, on the one hand it is possible to employ Apache Kafka for real-time data analysis of sensor data with a very high throughput. On the other hand, MQTT is preferably used in low-bandwidth and high-latency environments which makes it an optimal candidate for single-board computers with CPU limitations. Even IoT devices can communicate directly with services in the environment via a Kafka REST proxy or MQTT. For example, services can subscribe to a topic and then collect data coming from these devices and propagate further actions. Updates of the current actions can be sent back to the devices as well.

In the following, two different *message system variants* are illustrated. Both examples demonstrate the scalability of the system while redundant brokers are provided and, thus, achieving the necessary load balancing, orchestrated for instance, by Kubernetes.

2.4.1 MQTT Message Bus

The MQTT broker is distributed on many nodes in the network to provide failsafe operations. This is called an MQTT broker cluster which logically acts as one logical broker. A load balancer is implemented to give each client a single point of entry when communicating over MQTT. As a result, each single MQTT broker is not exposed directly to the clients. Moreover, the load balancer decides, based on different measurements (e.g., availability, capacity, and so on), which client should connect to which broker. If the network load increases, Kubernetes can deploy more MQTT broker inside a cluster to compensate high network loads and requests. The MQTT client itself will not notice that as it is using this service via the load balancer.

2.4.2 Kafka Message Bus

Apache Kafka[4] is a distributed messaging system, where *Apache Zookeeper*[5] is used as a load balancer to coordinate a Kafka cluster consisting of many Kafka brokers (that is, a node in a cluster). A Kafka broker manages the publishing and receiving of messages associated to topics for several consumers and producers. Regarding the communication of IoT devices with our presented system, a *Kafka REST Proxy*[6] can be utilized. REST is platform-agnostic, thus, enabling almost every embedded computer to send HTTP requests. The REST proxy provides an interface to a Kafka cluster.

2.5 Service Composition and Orchestration

The task of the orchestration layer in conjunction with OSGi includes the maintenance and extension of services on-demand. Thus, guaranteeing the flexibility and scalability of the system as required in the introduction of Section 2.

Single services can be deployed on any device on-demand assuming the necessary device requirements are met. This enables services to request dependencies from remote devices as if they were running in the same JVM. The orchestration layer contains a *service registry* which manages all deployed services of the different devices. Since services can specify dependencies to other registered services, the task of the service registry is to make the dependencies available

[4]https://kafka.apache.org/
[5]https://zookeeper.apache.org/
[6]https://github.com/confluentinc/kafka-rest

to other services. Therefore, the services are registered first to resolve the interdependencies between services later and to provide them accordingly.

For the presented 3D mouse case study (see Section 3), the individual components of the whole application (e.g., sensor data filtering and inverse kinematics calculation) are deployed on different devices depending on the device's performance or locality. This enables the deployment of a service on a device near the physical location where the action takes place (e.g., actuator responsible for moving the robotic arm).

3 A CASE STUDY: 3D MOUSE FOR ROBOTIC CONTROL

Robotic co-working is becoming an important aspect when humans and robots must work together in complex environments (Aßmann et al., 2017). Robots still do have very limited knowledge of their surroundings when they are brought into new environments (de Rengervé et al., 2011), for instance, in manufacturing, the automotive industry or the medical sector. To gain the necessary knowledge via on-line learning methods is a slow approach (de Rengervé et al., 2011), and therefore often not appropriate for automating processes in manufacturing nowadays. Primarily, the objective is to reduce the costs by accelerating the processes considering minimal transitional and implementation time. So far, robots were programmed directly without human interaction. However, this is a time-consuming and costly process where the results often do not generalise well enough within changing environments (Huang et al., 2015).

Therefore, programming the robot by imitation is an often used paradigm—also known as Programming by Demonstration (PbD) (Billard et al., 2008) or Learning from Demonstration (LfD) (Argall et al., 2009) in the literature—which is a much more preferable and appropriate solution to the mentioned problem (Bakker and Kuniyoshi, 1996; Dillmann et al., 2000; de Rengervé et al., 2011). A conceptual framework for robot imitation was proposed by (Bakker and Kuniyoshi, 1996), which states that an agent must contain the three fundamental processes to imitate an action from a teacher: *observation*, *representation* and *reproduction*. This allows the integration and migration of robots into new environments to operationalise them *immediately*. Especially for such scenarios real-time requirements must be guaranteed.

Regarding the PbD paradigm, we describe the construction of a low-cost device (functioning as 3D mouse to control the robot) and the corresponding near real-time system using our proposed reference architecture.[7,8] As a result, the device's motions (that is, the motion of a user) are instantly imitated by the robot without learning involved. The use of this 3D mouse is illustrated in Figure 3 which represents a point in space, a so-called *vectorial cursor*. The device captures the user's movement in mid-air and controls the robot's end effector. The presented 3D mouse is self-contained without the need for transmitters or receivers to detect signals in an environment (e.g., a smart room). The device's coordinates are described by the three-dimensional position vector $\mathbf{x} = [r, \theta, \phi]^\intercal$ in spherical coordinates.

3.1 Experimental Equipment

3.1.1 Cube-It

The Cube-It is regarded as an intelligent thing and serves as an abstract IoT device. It has the form of a cube where the housing is made out of cardboard with a dimension of $100\,\mathrm{mm} \times 100\,\mathrm{mm} \times 100\,\mathrm{mm}$ ($H \times W \times D$). A Feather M0 from Adafruit is used as portable microcontroller board with an ATSAMD21G18 processor running at 48 MHz with 3.3 V power (see Figure 4a).

Connected to the Feather M0 is the BNO055, a 9-DOF sensor to acquire necessary orientation value along two axes, namely ϕ and θ. The sensor values are sent via the integrated WiFi chip. Further, an additional IMU is integrated into the Cube-It. We are using the x-OSC NGIMU to measure the radial distance in relation to the user's position. The x-OSC NGIMU has its own WiFi module to send data via the Open Sound Control (OSC) (Wright, 2005) Protocol.

On the one hand, this architecture of the Cube-It allow us to send data via two independent WiFi clients, and on the other, the real-time system enables independent processing of these two data channels, thus, allowing the continuous operation of the robot at least in one spatial dimension in case one of the components fail.

Now, we explain how the *sensor data* of the Cube-It is used to acquire all three elements of the position vector. The Cube-It serves as an input device representing a vectorial point in mid-air which is updated by the user's motions. Let us define a 3-dimensional

[7]We are speaking about near real-time systems as the motion of the robot will always lag behind the motions of the user in this scenario, even when it is kept very small. The reason is, we first must compute the current position of the 3D mouse, then transmit the data using the system, and finally, the robot can be moved so that it follows the target.

[8]https://www.youtube.com/watch?v=GDY0dwD3ntU

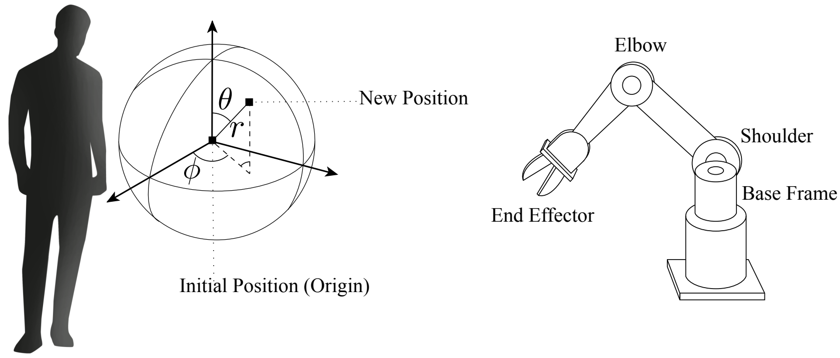


Figure 3: Handling of the 3D mouse. The position of the mouse in mid-air is mapped to the end-effectors position. The two black squares on the left-hand side denote the initial and the new position of the 3D mouse. The initial position of the device also represents the origin of its coordinate space. The translation of the device is described by the vector $[r, \theta, \phi]^\intercal$ which is necessary to control the end effector.

position vector $\mathbf{x} = [r, \theta, \phi]^\intercal$ describing a point in a spherical coordinate system. This point is a local representation of the robot's end effector. The origin of this system can be any point relative to the user's body preferably the half arm's length (as this is the most natural position to use the 3D mouse). The height is an irrelevant parameter due to the use of spherical coordinates; thus, the 3D mouse is used in mid-air independently from the height. The sensors deliver orientation information and acceleration data. Both angular values, ϕ and θ, are gathered by the orientation sensor. The radius r is determined by computing the magnitude of the displacement in space, provided by the acceleration data of the IMU, where the origin is the position of the device relative to the user's body in the xy-plane.

3.1.2 UR10

We use the UR10 from Universal Robots[9] for our experimental validation (see Figure 4b). For this case study we use the following three joints: the base, shoulder and elbow of the UR10. The company develops co-robots and provide 6-axis robot manipulator arms of different sizes. Currently, two production lines exist, where each robot in its line has a different payload and reach, but they share the same features. The robot can be customized with various end effectors, accessories, and software.

The UR10 has a maximal range of action of approximately 1300 mm. Moreover, each joint of the robot has a working range $\pm 360°$ with a maximum speed of $\pm 120/\text{Sec}$. Each joint can be controlled individually, or in parallel together with other joints.

[9]https://www.universal-robots.com/

3.2 Deployed Services

In this section, we describe the individual services of our example application scenario to steer the robot (see Figure 5).

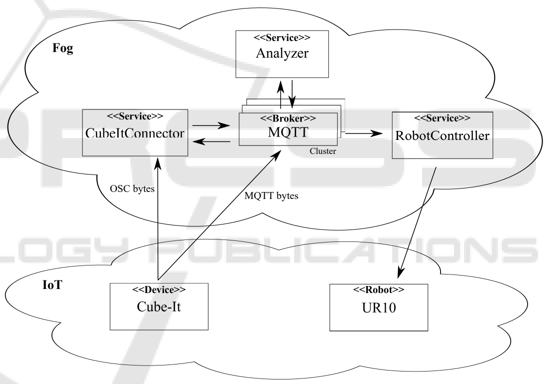
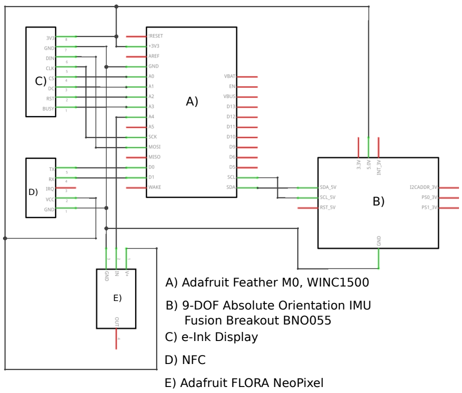


Figure 5: Implementation variant of the reference architecture as illustrated in Figure 1. Shown are the fog (top) and IoT layer (bottom). The fog layer consists of the distinct services centred around the MQTT broker, and the IoT layer comprises the Cube-It and UR10. The MQTT broker is used for communication between and inside each layer. Additionally, the Cube-It communicates over the OSC protocol with the `CubeItConnector` service directly.

Services contain certain parts of the whole functionality described by the internal model of the 3D mouse. These services are distributed on the different edge or fog devices in the local network allowing the data processing near devices which are producing the data. Thus, connecting the edge and IoT layer. With reference to the proposed architecture (see Figure 1), we only use one MQTT broker for the realisation of the message bus. The orchestration layer utilises Kubernetes, which monitors the state of the broker and in case of a failure, it will restart the broker.

First, the Cube-It transmits data via MQTT. For



(a) The representation of the electronic circuit of the Cube-It is shown. The x-OSC NGIMU is not integrated into the depicted circuit itself but inside the housing of the Cube-It.

(b) Image of the UR10 in use for the experimental demonstration.

Figure 4: Equipment used in our case study: A Cube-It, representing the 3D mouse, and the UR10.

that, the MQTT client of the Cube-It directly communicates with the MQTT broker. We created the two topics `o/orientation` and `o/acceleration` to send the angles and acceleration values of the Cube-It in separate channels, respectively. After the broker receives the message, it forwards it to the `CubeItConnector` service. The data format of the sensor readings (i.e., the sensor model) is specified with Google's Protocol Buffers Format. All services rely on the same data model. To clarify, the generated code from the model is used within all services of the application.

We defined two message formats, on the one hand for the orientation data, on the other for the acceleration data. Each message contains the current state of the Cube-It for a single time step. The message for the orientation contains angle values for all three axes, a "face" property (indicating the upwards pointed surface of the device, perpendicular to the floor), and three distinct time properties storing the sending, receiving and processing time. The message format for the acceleration data of the Cube-It gathered by the integrated IMU (see Section 3.1) is defined analogously to the orientation message format. In this case, the OSC protocol is used to transmit the data over user datagram protocol (UDP) to the `CubeItConnector` service for further processing which implements an OSC listener.

Secondly, as the `CubeItConnector` receives the data packages, they are forwarded to the `Analyzer` service. Before that, the connector validates the data and performs some initial pre-processing. The `Analyzer` service contains the whole functionality of the 3D mouse model and computes the inverse kinematics.

Third, the results of the computations are sent to the `RobotController` service. It contains the control classes to interact with the UR10 via TCP/IP over the network. The IP address of the robot is stored in a configuration file which can be changed at runtime. A simulation can be run, or the actions can be transferred directly to the physical instance of the UR10.

3.3 Summary

Figure 1 presented the components of our data-driven and service-oriented reference architecture. From our implementation in Figure 5 it is observed that the initial objectives *SoC*, *distribution*, and *availability and scalability* are achieved.

Scalability and availability are achieved through the orchestration layer. The QoS monitoring service within Kubernetes detects degrading or failed services. On that basis, appropriate load distribution for services of an IoT application can be carried out which also includes internal services such as the MQTT brokers.

The implemented OSGi architecture covers the updatability aspect. Moreover, it provides the basis for a service-oriented design. Thus, an IoT application encompasses modular software components which can be added, changed, or removed at runtime without stopping the system. Fixing bugs and testing becomes more straightforward. Consider the following use case examples. If we want to include a robot simulator, we can do so without affecting other components. If the robot should be exchanged, we only have to swap the controller service. The analyzer and connector remain the same. Adding a new input device is accomplished by only changing the data model within the connector service to conform the input parameters of the analyzer service. If we want to add motion prediction we have to add a new component next to analyzer where the rest is not touched.

4 CONCLUSION

This work aimed to create a usable software architecture of a near real-time system following fog computing principles.

Therefore, we proposed a fog computing architecture for service-oriented IoT applications based on the OSGi standard, allowing dynamic deployment of services that act as IoT application components. Services can be dynamically updated or injected on-the-fly without restarting the whole application. Thus, the proposed software architecture makes it very convenient to deploy and distribute the changes back into the edge network. Furthermore, the architecture allows dynamic (permanent or ad-hoc) integration of a large number of services and IoT devices.

Following our reference architecture, we showed an implementation variant and demonstrated the usefulness for a fog computing scenario. The Cube-It, representing the 3D mouse, was built to control the movement of a robot based on the motion of a user. On the basis of the data-driven hardware models for sensors and actuators, our architecture allowed to virtually interchangeably use any IoT device with minimal effort regarding the configuration.

Future Work. First, we plan to conduct more experiments to evaluate our architecture. In this work we have not addressed the performance of the architecture. A comparative analysis of the performance (regarding high availability and resilience of node failures) between the proposed implementation and existing architectures is left for future work.

Another interesting open issue to investigate is the behavior of the system under dynamic integration of a large number of services and IoT devices.

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REFERENCES

Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., and Ayyash, M. (Fourthquarter 2015). Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. *IEEE Communications Surveys Tutorials*, 17(4):2347–2376.

Argall, B. D., Chernova, S., Veloso, M., and Browning, B. (2009). A survey of robot learning from demonstration. *Robotics and Autonomous Systems*, 57(5):469–483.

Aßmann, U., Piechnick, C., Püschel, G., Piechnick, M., Falkenberg, J., and Werner, S. (2017). Modelling the World of a Smart Room for Robotic Co-working. In *Model-Driven Engineering and Software Development*, Communications in Computer and Information Science, pages 484–506. Springer, Cham.

Bakker, P. and Kuniyoshi, Y. (1996). Robot See, Robot Do : An Overview of Robot Imitation. In *In AISB96 Workshop on Learning in Robots and Animals*, pages 3–11.

Billard, A., Calinon, S., Dillmann, R., and Schaal, S. (2008). Robot Programming by Demonstration. In *Handbook of Robotics*, pages 1371–1394. Springer Berlin Heidelberg.

Bonomi, F., Milito, R., Natarajan, P., and Zhu, J. (2014). Fog Computing: A Platform for Internet of Things and Analytics. In Bessis, N. and Dobre, C., editors, *Big Data and Internet of Things: A Roadmap for Smart Environments*, Studies in Computational Intelligence, pages 169–186. Springer International Publishing, Cham.

Bonomi, F., Milito, R., Zhu, J., and Addepalli, S. (2012). Fog Computing and Its Role in the Internet of Things. In *Proceedings of the First Edition of the MCC Workshop on Mobile Cloud Computing*, MCC '12, pages 13–16. ACM.

de Rengervé, A., Hirel, J., Andry, P., Quoy, M., and Gaussier, P. (2011). On-line learning and planning in a pick-and-place task demonstrated through body manipulation. In *2011 IEEE International Conference on Development and Learning (ICDL)*, volume 2, pages 1–6.

Dillmann, R., Rogalla, O., Ehrenmann, M., Zöliner, R., and Bordegoni, M. (2000). Learning Robot Behaviour and Skills Based on Human Demonstration and Advice: The Machine Learning Paradigm. In Hollerbach, J. M. and Koditschek, D. E., editors, *Robotics Research*, pages 229–238. Springer London, London.

Evans, D. (2011). How the Next Evolution of the Internet Is Changing Everything.

Huang, D. W., Katz, G., Langsfeld, J., Gentili, R., and Reggia, J. (2015). A virtual demonstrator environment for robot imitation learning. In *2015 IEEE International Conference on Technologies for Practical Robot Applications (TePRA)*, pages 1–6.

ISO/IEC (2016). ISO/IEC 20922:2016 - Information technology – Message Queuing Telemetry Transport (MQTT) v3.1.1. https://www.iso.org/standard/69466.html.

Light, R. A. (2017). Mosquitto: Server and client implementation of the MQTT protocol. http://joss.theoj.org.

Liu, P., Willis, D., and Banerjee, S. (2016). ParaDrop: Enabling Lightweight Multi-tenancy at the Network's Extreme Edge. In *2016 IEEE/ACM Symposium on Edge Computing (SEC)*, pages 1–13.

McAffer, J., VanderLei, P., and Archer, S. (2010). *OSGi and Equinox: Creating Highly Modular Java Systems*. Addison-Wesley Professional.

Negash, B., Rahmani, A. M., Westerlund, T., Liljeberg, P., and Tenhunen, H. (2016). LISA 2.0: Lightweight internet of things service bus architecture using node centric networking. *Journal of Ambient Intelligence and Humanized Computing*, 7(3):305–319.

Rellermeyer, J. S. and Alonso, G. (2007). Concierge: A Service Platform for Resource-constrained Devices. In *Proceedings of the 2Nd ACM SIGOPS/EuroSys European Conference on Computer Systems 2007*, EuroSys '07, pages 245–258, New York, NY, USA. ACM.

Sarkar, C., N, A. U. N. S., Prasad, R. V., Rahim, A., Neisse, R., and Baldini, G. (2015). DIAT: A Scalable Distributed Architecture for IoT. *IEEE Internet of Things Journal*, 2(3):230–239.

Willis, D. F., Dasgupta, A., and Banerjee, S. (2014). ParaDrop: A Multi-tenant Platform for Dynamically Installed Third Party Services on Home Gateways. In *Proceedings of the 2014 ACM SIGCOMM Workshop on Distributed Cloud Computing*, DCC '14, pages 43–44, New York, NY, USA. ACM.

Wright, M. (2005). Open Sound Control: An enabling technology for musical networking. *Organised Sound*, 10(3):193–200.