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Supporting smart construction with dependable edge computing infrastructures and applications

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ABSTRACT

The Internet of Things (IoT) such as the use of robots, sensors, actuators, electronic signalization and a variety of other Internet enabled physical devices may provide for new advanced smart applications to be used in construction in the very near future. Such applications require real-time responses and are therefore time-critical. Therefore, in order to support collaboration, control, monitoring, supply management, safety and other construction processes, they have to meet dependability requirements, including requirements for high Quality of Service (QoS). Dependability and high QoS can be achieved by using adequate number and quality of computing resources, such as processing, memory and networking elements, geographically close to the smart environments. The goal of this study is to develop a practical edge computing architecture and design, which can be used to support smart construction environments with high QoS. This study gives particular attention to the solution design, which relies on latest cloud and software engineering approaches and technologies, and provides elasticity, interoperability and adaptation to companies' specific needs. Two edge computing applications supporting video communications and construction process documentation are developed and demonstrate a viable edge computing design for smart construction.

1. Introduction

Millions of new Internet-connected devices commonly known as the Internet of Things (IoT) have been developed in the past years. According to Gartner, Inc. [1] their number will rise up to 20 billion by 2020. These devices include sensors, actuators, smartphones, signalization, robots and so on, and are being developed to facilitate smart, automated, secure and sustainable environments and working processes in various industrial sectors including construction.

The construction process is commonly known as a very complex process which requires a lot of automation. Smart application possibilities include construction site automation, robots assisted construction, infrastructures monitoring, safety monitoring, home automation and many more.

Some applications require a lot of networking and processing support, such as coordination and logistic operations for robots, videostream analysis for infrastructure monitoring and safety signalization at construction sites. Frequently, IoT devices run on batteries and are without a strong processor. This usually leads to the necessity to offload computations to nearby microservers and datacenters, where higher frequency processors can be obtained. Generally, the network latency, bandwidth, network throughput, round trip time and similar QoS metrics are important in the IoT applications to achieve higher dependability.

Hence, there are significant technical requirements that must be met by smart construction applications to make them of true business value. The first necessary step in the development process for smart applications is therefore the identification of their detailed technical requirements. Requirements analysis must take into consideration QoS attributes such as network related metrics and performance, and other nonfunctional requirements, such as reliability, availability, security, safety and similar, which are commonly known in systems engineering as dependability attributes.

A major obstacle for the introduction of advanced IoT applications in the construction sector at the moment is their unacceptable Quality of Service (QoS) hindering possibilities for real-time operation. In the past years, a variety of case studies for IoT applications in the construction sector have been published [2–5]. Indeed, such applications can only achieve their business value, if they meet high QoS standards, that is, dependability requirements.

Significant networking, processing and memory resources are required by smart applications, for example, to dynamically process data coming from cameras, sensors, robots and smartphones and to provide feedback and control loops for signalization and actuators. In order to

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build an adequate approach, we can rely on existing cloud services designs in general, and dependability solutions in particular. Mell et al. [6] define cloud computing as a model, which enables universal, on-demand network access to shared pool of computing resources, such as: networks, servers, storage, applications and services that can be rapidly provisioned and managed with minimal effort. Such resources can be obtained dynamically from cloud providers.

From technology viewpoint, in order to be able to address the requirements of smart IoT applications, there are some new developments in the cloud computing domain, which may be appropriate for latency-sensitive applications. Edge and fog computing as specific areas of cloud computing intend to improve the design of cloud applications by organising processing closer to the data sources at the edge of the network [7], thus, reducing communications latency and improving reliability and other aspects. Hence, due to the nature of the edge computing concept, it may be necessary for construction companies to invest in some computing and networking infrastructures to be able to support the operation of smart IoT applications.

Recently, two new initiatives for interoperability standards have emerged – the Cloud Native Computing Foundation (CNCF) [8] and the OpenFog Consortium [9]. These initiatives rely on a variety of new technologies and projects' outcomes, including: specific operating systems for edge computing, such as CoreOS [10] and RancherOS [11] that can be installed on devices such as microservers, routers and Raspberry PIs; technologies for container based virtualization, such as Docker [12]; technologies for container orchestration, such as Kubernetes [13] and Mesos [14]; and advanced new software engineering tools, such as Fabric8 [15]. Nowadays, all these technologies can be used to build and operate elastic and interoperable IoT applications. The present study seeks to understand their utility in the context of various potential smart construction applications.

Therefore, the goal of this work is to assess the requirements of potential smart construction IoT applications and provide a practical edge computing architecture and design for their implementation. This requires the investigation of existing smart construction applications developed before the existence of the above-mentioned edge and fog interoperability initiatives.

Based on the number of ongoing activities which need smart IoT support, the requirements for underlying cloud and edge computing infrastructures may dynamically change. This, in turn, may lead to under or over occupancy of computing resources and consequently to unacceptable variations in the obtained QoS. Our design should therefore also address the requirement for cost effectiveness of the edge computing solution.

In order to demonstrate and test the dependability of the edge computing design, two IoT applications have been developed, covering construction video communications and building process documentation. Common to these two applications are their requirements to operate with large quantities of data, including data streams. This translates to high QoS requirements which must be met for their successful operation. The smart application design combines the benefits of edge computing, such as on demand self-service, broad network access, elasticity, low operation cost and adaptability to dynamically changing business needs.

The paper is structured as follows. Section 2 presents an overview of related works in the smart construction domain. Section 3 presents the approach, the system dependability requirements and the new edge computing architecture and design that can be used to support smart IoT applications. The deployment and implementation of the two applications, together with experimental results are presented in Section 4. Section 5 overviews some potential IoT application areas. Finally, Section 6 concludes the paper and reveals further development plans.

2. Related works – smart construction application opportunities

An initial review of the literature related to edge and fog computing applications in the construction domain revealed a gap. Following is a brief account of several application areas where new IoT edge computing applications would be greatly needed. Particular attention was paid to identify the technical requirements of potential applications, particularly the necessary QoS and the required computing infrastructures for their operation. Potential application areas that were investigated included construction site management, material supply management, security and safety of construction sites, real-time information sharing and communication.

Yuan et al. [16] propose a set of Cyber-Physical Systems (CPS) to prevent failure of temporary structures through real-time monitoring. Their solution is supported with a mobile application and a cloud-based database. Ren et al. [17] deal with the problem of collision accidents between cranes and immobile obstacles, which they try to reduce. Their solution is a real-time anti-collision system that warns of potential collisions and implements adequate safety strategies. The works [18] and [19] present solutions for safety at construction sites preventing collisions between building equipment as well as plant-pedestrian collisions by using different monitoring technologies. Their solution relies on the use of Radio-Frequency IDentification (RFID) tags, warning devices and is supported by a communication protocol and a user interface. This work of Jegen-Perrin et al. [20] describes a method to estimate the working area, and using RFID sensors to prevent possible collision accidents. It proposes the use of a camera-and-screen system to prevent the plant-pedestrian accidents with method to improve drivers visibility through real-time video monitoring. Time-critical requirements are common for all these applications.

In order to improve the construction process a variety of supply management and communication software prototypes have been proposed [21–23]. Prasad et al. [24] describe that material handling significantly affects the construction process, therefore they provide a software prototype for handling construction materials in a cost-effective manner with low human intervention. Wang et al. [25] provide a web-based solution that combines RFID technology and smart devices to enhance the effectiveness of data and information sharing at construction sites. Kim et al. [26] addressed in their study solutions for site monitoring, task management and real-time information sharing through a multi-tier computing infrastructure. Applications in supply management and communication may therefore offer significant improvements in the overall construction process. Common for these applications are high dependability requirements, including service availability, reliability, safety, security, portability, maintainability and scalability.

Lack of communication at construction sites often causes accidents and may lead to many severe on-site problems and delays in the construction process. There are many communication solutions available on the market, however, according to the review results presented by Shi et al. [27] the existing solutions for on-site communication between construction teams and site offices are error prone. Web-based technologies have also been considered as solutions that could improve the process. The following works [28–32] present potential benefits of using Web technologies and cloud infrastructures for such applications. The authors, however, mainly provide solutions for centralized processing and storing massive amounts of construction site data in databases in the cloud. However, real-time applications are obviously more challenging and have not been addressed.

Several studies focus on the use of various IoT devices in construction. The authors [4] presented how the IoT and related standards can improve the construction management system. Bai et al. [33] introduced tower crane safety supervising system based on IoT, which effectively supervises the tower production process safety. Most IoT applications developed so far have been optimized to run either locally or on Web-servers, not implementing any solutions to decrease the