Cloud Computing Ontologies: A Systematic Review

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***Abstract*—The main objective of this study is to obtain a holistic view of Cloud Computing ontologies, their applications and focuses. The identification of primary studies in this systematic review is based on a pre-defined research protocol with a research question, inclusion and exclusion criteria and a search strategy. We summarize the selected studies into four main categories: Cloud resources and services description, Cloud security, Cloud interoperability and Cloud services discovery and selection. The analysis of the included studies indicates a number of challenges and topics for future research, including those specifically related to using ontologies to improve security and interoperability of Cloud Computing offerings.**

Keywords—Cloud Computing; ontology; systematic review; Cloud service

I. Introduction

Cloud Computing has become a new paradigm for the provision of computing infrastructure, platform or software as a service. Its main benefits are flexibility, pay-per-use model and significant cost reduction. Linthicum [1] concludes that the most comprehensive definition of the aforementioned paradigm is that provided by NIST. According to this definition, "Cloud computing is a pay-per-use model for enabling available, convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications, services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" [1]. The minimum definition of Cloud Computing must contain scalability, pay-per-use utility model and virtualization [2]. Cloud Computing is primarily a new business paradigm [3] that enables on-demand access, elasticity, pay-per-use, connectivity, resource pooling and abstracted infrastructure [4].

There are a lot of Cloud Computing review papers in the current literature but to date no systematic review of Cloud Computing ontologies has been published. Therefore the primary aim of our research is to systematically select and review published work and provide an overview of Cloud Computing ontologies, their types, applications and focuses. The following research questions are stated: What are the main focus and application contexts of Cloud Computing ontologies covered in the scientific literature? What is the impact of the studies to scientific and professional community?

This paper proceeds as follows. Firstly, in Section 2, we describe the research method used in this review. Section 3 contains the overview data concerning the included studies. In the Section 4 we provide a detailed description of relevant reviewed papers and classify them into appropriate categories according to topics. Then, Section 5 presents a synthesis of this systematic review. Our conclusions are presented in the last section.

II. Research Method

Our research uses a systematic review method [5], which is a formalized process to assess and interpret all available research related to a specific research question. Guidelines that address specific problems of software engineering research are introduced in [5]. A systematic review has three main phases: planning the review, conducting the review and reporting the review.

We developed a review protocol in the planning phase. The background and the research question are specified in the introduction of our paper. Only full papers in English from peer-reviewed journals and conferences published from 2008 to 2011 were considered. Studies that are not related to the usage of ontology in Cloud Computing were excluded. In cases where several duplicated studies were found that existed in different versions, only the most complete version of the study was included. We focused on searching Google Scholar and the following electronic scientific databases: ScienceDirect, Current Contents, IEEE Xplore, SpringerLink and ISI Web of Science. These databases had been chosen since they provide the most important journals and conference proceedings covering Cloud Computing and ontology engineering. The following search term was used to find relevant studies: Cloud Computing AND ontology. Irrelevant studies were excluded based on the analysis of their titles, abstracts and keywords, whereas primary studies were obtained based on full text read. The search process was performed in November 2011, during which a total of 463 publications were identified. After filtering the publications list by reading titles, abstracts and keywords, full text reading of the articles that had not been excluded was performed to ensure that the content is related to our research question. Finally, 24 studies were identified as primary studies. Data extraction and synthesis were done by reading the full text of these 24 studies and extracting relevant data to Excel spreadsheets.

III. Overview Data Concerning Selected Studies

In this section we describe the sources of publication and the citation status of the selected studies. Most of these studies were published in conference proceedings, book chapters and journals. Table I. provides an overview of the distribution of the studies and the number of studies from a particular source type.

TABLE I. DISTRIBUTION PER PUBLICATION SOURCE TYPES

Source	Count
Conference proceedings	13
Book chapters	5
Journals	5
Workshops	1
Total	**24**

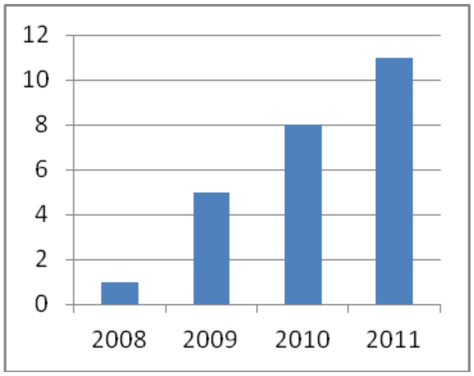

Figure 1. Number of studies by year of publication.

TABLE II. ACTIVE RESEARCH COMMUNITIES

Institution	Number of studies
Gwangju Institute of Science and Technology, South Korea	3
Wuhan Univ. of Technol., China	2
Victoria Univ. of Wellington, New Zealand	2

The obtained distribution is in line with expectations since Cloud Computing is a relatively new paradigm. The citation rates for the included studies were obtained from Google Scholar. The citation rates of the studies are quite low (most studies <10 citations). This result is in line with expectations since all the initially selected studies were published from 2008 to 2011, and 75% of those that were eventually included were published in last two years. According to Google Scholar data, the most cited publications from our selected set of studies are [6] with 191 citations and [7] with 38 citations. When the year of publication of the papers is concerned (Figure 1), we noticed an upward trend in the number of relevant publications about Cloud Computing ontology. In the selected set of studies we also looked for the authors' affiliation details in order to identify active research communities involved in work related to Cloud Computing ontologies (Table II.).

IV. RESULTS

Our examination of the selected studies was based on their similarities in terms of the main focus and application of Cloud Computing ontologies. We identified four main categories: Cloud resources and services description, Cloud security, Cloud interoperability and Cloud services discovery and selection.

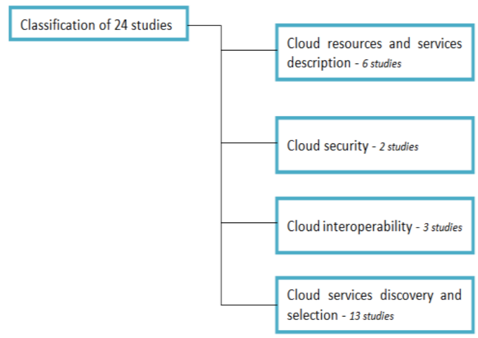

Figure 2. Classification of included studies.

Figure 2 illustrates these categories while also specifying their distribution across studies. The identified categories will be elaborated in the following subsections.

A. Cloud Resources and Services Description

The studies in this category use the Cloud ontologies to describe Cloud resources and services, classify the current services and pricing models or define new types of Cloud services.

One of the first attempts to establish a detailed Cloud ontology was presented in [6]. In that paper the authors proposed an ontology which demonstrates a dissection of the Cloud into five main layers: applications, software environments, software infrastructure, software kernel and hardware. Each layer encompasses one or more Cloud services which belong to the same layer if they have equivalent levels of abstraction. The authors of the ontology in [6] also discussed each layer's strengths, limitations and their dependency on preceding computing concepts.

Weinhardt et al. [7] proposed a Cloud business ontology model to classify current Cloud services and pricing models. Their ontology consists of three layers: infrastructure, platform and application as a service. Cloud users and providers can use it to map the existing Cloud services and set pricing schemes.

Bohm et al. [8] suggested various definitions of Cloud Computing, its billing models and a systematic description of its major actors and value network. They also reviewed the definitions, models and ontologies from the existing literature.

The concept of ontology as a service was proposed in [9]. Ontology as a service (OaaS) is a service where Cloud vendors provide the application and infrastructure to tailor the source ontology to the users' requirements. The authors of the study reported in [9] elaborated ontology extraction and sub-ontology merging process.

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Sheng-Yuan et al. [10] proposed an ontology-supported ubiquitous interface agent and described the interaction with the backend information agent system in Cloud Computing.

A formal catalog representation of Cloud services was proposed in [11]. In this paper, Deng et al. introduced a range of Cloud services and their processes modeled by means of ontological representation.

B. Cloud Security

The studies in this category use ontologies to describe and improve Cloud security.

Takahashi, Kadobayashi and Fujiwara [12] built the ontology for cyber security operational information and applied it to Cloud Computing. Since the essential changes of cyber security information in Cloud Computing are data-asset decoupling, composition of multiple resources and external resource usage, they included data provenance and resource dependency information into their ontology.

The architecture of a deployed service in the Cloud Computing environment used for malware detection was presented in [13]. The authors used the ontology for malware and intrusion detection that represents the signatures for known and novel attacks as well as an ontological model for reaction rules creating the prevention system.

C. Cloud Interoperability

One of the biggest obstacles of Cloud Computing is provider lock-in that can be solved by means of interoperable Cloud services. The studies in this category show how to use ontologies to achieve interoperability among different Cloud providers and their services.

The FP7 mOSAIC project is aimed at creating and exploiting an open-source Cloud application programming interface and a platform for developing multi-Cloud oriented applications. The mOSAIC Cloud Ontology is described in [14]. The concepts in this ontology were identified by analyzing standards and proposals from literature and will be used for semantic retrieval and composition of Cloud services.

Bernstein and Vij [15] presented the InterCloud Directories and Exchanges mediator to enable connectivity and collaboration among Cloud vendors. Their ontology of Cloud Computing resources intended for facilitating work with heterogeneous providers of Cloud Computing services was defined using RDF.

A method for semantic interoperability aggregation in requirements refinement and a metric framework for calculating semantic interoperability capability based on ontologies are proposed in [16]. This methodology can provide a semantic representation mechanism for refining users' requirements in the Cloud Computing environment.

D. Cloud Services Discovery and Selection

This category consists of the studies that use ontologies to discover and select the best Cloud service alternative.

Along with a lack of standard definitions of resource requirements, managing Cloud resources implies resource information management issues and resource allocation compatibility problems. As a solution to the aforementioned problems, Yoo et al. [17] proposed a resource virtualization method using ontology.

Wang and Li [18] introduced the basic principles of the HCCloud (Heterogeneous Computing Cloud) design. The HCCloud is their architecture for the deployment and management of distributed applications in the Cloud where users can access services based on their requirements regardless of where the services are hosted. The resource selection mechanism starts with the user's requirements, calculates the similarity between resources and a particular candidate in the database of the Cloud resource ontology and ranks candidate resources accordingly.

Han and Sim [19] presented a Cloud service discovery system that uses Cloud ontology to determine the similarities between and among services. It is an agent-based discovery system that enables reasoning about the relations of Cloud services using three types of similarity reasoning to assist users in searching available Cloud services more efficiently. Their Cloud ontology consists of concepts of different Cloud services for IaaS (infrastructure as a service), PaaS (platform as a service) and SaaS (software as a service).

Zhou, Yang and Hugill [20] introduced a novel approach to reengineering enterprise software for Cloud Computing. They proposed the ontology for enterprise software and then partitioned it to decompose enterprise software from legacy system into potential service candidates during migration to the Cloud Computing environment.

In their study, Kang and Sim [21] proposed a Cloud ontology to semantically define the relationship among different Cloud services. The similarity among Cloud services is determined using concept similarity reasoning, object property similarity reasoning and data type property similarity reasoning. They also presented their own Cloud service search engine that uses the defined ontology. Users can specify functional, technical and cost requirements, and the search engine returns the list of relevant Cloud services. Sim [22] proposed the development of software agents for Cloud service discovery, service negotiation and service composition. An agent-based search engine for Cloud service discovery consists of a service discovery agent that uses the defined Cloud ontology and multiple Cloud crawlers. In the aforementioned study, Sim [22] also devised a complex Cloud negotiation mechanism and adopted a focus selection contract net protocol and service capability tables to automate Cloud service composition.

In [23] Dastjerdi, Tabatabaei and Buyya presented an architecture using ontology-based discovery to provide QoS aware deployment of virtual appliances on Cloud IaaS services. Virtual appliances are sets of virtual machines including operating systems, pre-configured and ready-to-run applications and embedded needed components. The proposed architecture can help users to deploy their virtual appliances on the most appropriate IaaS providers based on their definition of QoS requirements.

Yun et al. [24] introduced a tele-management system using a Cloud Computing platform for ubiquitous city. Ontology was used for context aware intelligence processing.

Semantic services discovery from the available Cloud providers is described in [25]. In this study, Wang et al. extended the Support Vector Machine (SVM)-based text clustering technique and proposed an iterative process to incrementally enrich domain ontology.

Ma, Schewe and Wang [26] extended their ASM-based model of Abstract State Services (ASSs) to a Cloud Computing model. They proposed a formalism of Clouds by federations of services and a description of Cloud services in form of ontology. These descriptions contain a technical description of services (types, pre- and post-conditions) and keywords which describe the application area and functionality of the annotated service.

The architecture to provide a semantic service for document management in Cloud Computing implemented by using techniques of web service and ontology was proposed in a book chapter by Wei and Junpeng [27].

In their paper, Ma, Jang, and Lee [28] proposed an ontology-based job allocation algorithm for a resource management system in Cloud Computing. They considered virtual machines as Cloud resources and built a Cloud ontology based on Cloud resource information and agreed SLAs (Service Level Agreements). The aforementioned ontology can be used to process complicated queries for searching Cloud resources. Its experimental results have verified that the ontology-based resource management system improves the efficiency of resource management for Cloud Computing when compared to the existing resource management algorithms.

The approach to developing semantic Cloud services which are annotated based on shared ontology was proposed in a book chapter by Chen, Bai, and Liu [29], along with a description of the usage of these annotations for semantics-based discovery of relevant Cloud services.

V. DISCUSSIONS

Research papers regarding Cloud Computing ontologies vary in terminology, descriptions and involved activities, but they also share a lot in common (focus, goal, application etc.). Our examination of the selected studies was based on their similarities in terms of the main focus and application of Cloud Computing ontologies. We divided them in the four categories: Cloud resources and services description, Cloud security, Cloud interoperability and Cloud services discovery and selection.

Since the bias in our selection of the studies to be included presented the main threat to validity of our research, we used a research protocol to define the research question, inclusion and exclusion criteria and our search strategy. The review protocol was prepared by the first author and reviewed by the other two authors.

Our review reveals that Cloud Computing ontologies are predominantly applied in the discovery and selection of the best service alternative in accordance with users' needs and the description of Cloud resources and services (80% of the relevant identified studies deal with these issues). The identified categories of themes provide an overview of Cloud Computing ontologies research as well as a basis for discovering possibilities for improvement in research and practice. Table III specifies the main achievements, limitations and challenges of these categories in the existing literature.

TABLE III. CURRENT STATE OF THE CLOUD COMPUTING ONTOLOGIES

Category	Achievements	Limitations and challenges
Cloud resources and services description	- general Cloud business ontology - dissection of the Cloud into layers - classification of the current Cloud services	- Cloud market is very dynamic, new Cloud services often emerge - detailed ontology of the Cloud resources and services is missing
Cloud security	- the ontology for cyber security operational information in Cloud Computing - the ontology for malware and intrusion detection deployed in the Cloud	- data and assets can be decoupled and manipulated independently in the Cloud Computing - external resources usage and composition of multiple resources - privacy and data security risks
Cloud interoperability	- the mOSAIC Cloud ontology that uses concepts from standards and proposals from literature to improve interoperability - ontology based Cloud Computing resources catalog to federate or interoperate resources	- lack of interoperability among Cloud Computing services - common Cloud API or an orchestration platform is currently not available (some on-going FP7 research projects such as mOSAIC plan to develop Cloud interoperability platforms) - detailed ontology focused on Cloud API resources and operations does not exists
Cloud services discovery and selection	- multiple Cloud services discovery and selection approaches were proposed	- user-friendly application for Cloud services discovery and selection is still missing

The analysis of the selected studies indicates a number of challenges and topics for future research based on identified limitations and challenges in the existing literature. The most promising area of future research is the use of ontologies to improve security and interoperability of Cloud Computing offerings, because the main obstacles of the Cloud Computing paradigm are provider lock-in and security/privacy issues. For example, interesting research challenge is using an ontology-based approach as a basis for creation of the mechanism to automatically determine and solve interoperability problems among two or more Cloud Computing services provided by different vendors. Ontologies can also be useful tool to annotate sensitivity of data and portions of data stored in Cloud services. Existing Cloud Computing ontologies are mostly general and detailed ontologies of each Cloud Computing layer (software as a service, platform as a service, infrastructure as a service) are still missing.

Besides for researchers, this systematic review might have implications for practitioners. They can use this review as a source in searching for relevant approaches for Cloud services discovery and selection. The identified limitations of the current literature can inspire programmers and Cloud users (e.g., development of user-friendly application for Cloud services discovery and selection).

VI. CONCLUSION

Cloud Computing is a new paradigm for the provision of computing infrastructure, platform or software as a service. The main objective of the systematic review presented in our paper is to obtain a holistic perspective of Cloud Computing ontologies, their applications and focuses. We identified 24 primary studies using the systematic review methodology described in [5].

The main focus and application contexts of Cloud Computing ontologies covered in the scientific literature are: Cloud resources and services description, Cloud security, Cloud interoperability and Cloud services discovery and selection. The studies in the first category use the Cloud ontologies to describe Cloud resources and services, classify the current services and pricing models or define new types of Cloud services. The Cloud security category shows how to use ontologies to describe and improve Cloud security. Cloud interoperability consists of the studies that use ontologies to achieve interoperability among different Cloud providers and their services. Finally, the fourth category comprises the studies that focus on discovery and selection of the best Cloud service alternative using the previously defined ontology.

The analysis of the selected studies indicates a number of challenges and topics for future research, including those specifically related to using ontologies to improve security and interoperability of Cloud Computing offerings. The main obstacles of the Cloud Computing paradigm are provider lock-in and security/privacy issues, which researchers can overcome by using an ontology-based approach. Practitioners can use our work to find existing approaches or develop new applications inspired by identified limitations of the currently available solutions.

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