Cloud Computing in Factory Automation: A Survey and Open Problems*

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***Abstract*—In this paper we focus on the usage of cloud computing technology in factory automations. We look at the state of the art in order to investigate the recent researches on this topic. We divide this topic into three main layers as follow. The first layer focuses on the usage of cloud computing in enterprise and resource planning of factory automations. The second layer deals with the high level control, while the third layer considers the usage of cloud computing in field level of automation. Moreover, in this paper we identify some open problems related to the mentioned three layers.**

I. Introduction

Recently the trend of using cloud computing in IT services has increased where computation and data are moved away from local computers to large data centers [1]. The cloud not only provides storage services, but also caters software, computing and data access for users. Commonly, end users may not require knowledge of physical location and the configuration of the system, which is one of the main profits of this technology [2]. Therefore, using the internet, applications and software can be delivered to the customers as services, leading to overall cost reduction for end users. Good examples of cloud computing providers are Amazon Web Service, Google and IBM, who implemented and launched cloud computing services in recent years [2].

The characteristics of cloud computing played a very important role to bring this new technology not only to the IT management, but also to the industry, in particular, to automation systems. Due to accessing the data and applications via available infrastructures (e.g., via web browsers), the cost of implementing the infrastructure for the customers has reduced significantly. This also includes less IT skills for implementation of the system [2]. Moreover, obtaining reliable services, sharing resources and costs among a large collection of end users, easier maintenance, and flexibility are the other motivations of using cloud in industry. However, there are many issues, such as security, still remain as concerns which delay adopting this technology in industry [3].

According to a model that is defined by the US National Institute of Standard (NIST), three types of services are recognized by cloud computing. These services include: (i) Software-as-a-Service (SaaS), (ii) Infrastructure-as-a-Service (IaaS), and (iii) Platform-as-a-Service (PaaS) [4]. Looking at the above mentioned features of cloud computing and the needs of factory automations, such as flexibility, agility and adaptivity, usage of different cloud service types in factory automation has become an interest. Therefore, many researches and eventually development have been done for different industrial platforms [5]. These researches include using cloud for home automation and mobile services [6] [7], electrical power dispatching control systems [8], manufacturing systems [9], SCADA systems [10] and using PLC control systems as a cloud service [11].

In this paper, we look at the state of the art, in particular, using the cloud computing technology in different automation systems. To the best of our knowledge, the researches in this area are focused on specific problems in the automation industry, i.e., by the moment of writing this paper we could not find any general proposed architecture to be used in automation systems. Therefore, in this paper, we identify the open problems and challenges in applying cloud computing services in automation systems.

The rest of the paper is organized as follow. Section II describes the background on cloud computing. Section III presents the state of the art on using cloud computing in automation systems, while Section IV identifies the open challenges and problems in this area. Finally, Section V concludes the paper.

II. Background

In this section, we describe some background related to two particular concepts. The first one is factory automation by focusing on new technological trends in that, whereas the second one is cloud computing technology.

A. *Factory Automation*

Factory automation is a huge industry. Work towards computer-integrated manufacturing (CAM) is dating back to the mid 1970s [12]. Main idea behind CIM was to split up different tasks within a manufacturing process into separate hierarchies. Those hierarchies represent the management levels of a company and are often shown as automation pyramid, as shown in Figure 1. The lower levels of the manufacturing pyramid represent the parts close to the shop floor like sensors, actuators, and fieldbusses. Automation controllers and PLC are located above that level. With each level the abstraction from the shop floor increases, ending with Enterprise Resource Planning (ERP) at the top of the pyramid. Different values are controlled on each level. The lower levels control physical

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values such as temperature, pressure and flow, whereas the higher levels are concerned with business values. On the other hand, different timing parameters can be associated with different levels. Where control loops in the lowest levels have cycle times of milliseconds, the highest levels have cycle times of days or weeks [13].

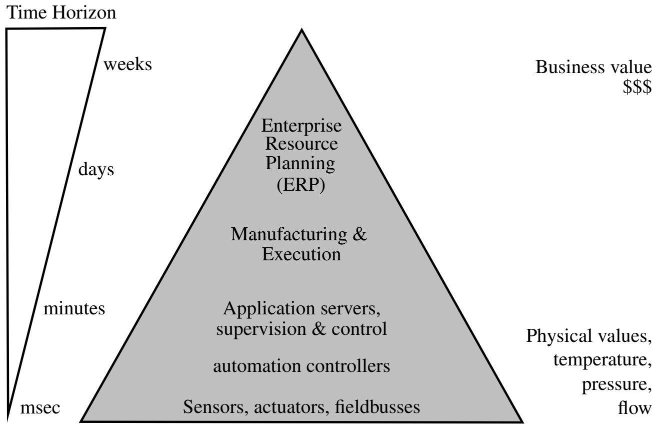

Fig. 1: Automation Pyramid (Figure 1-2 [13])

The different cycle times at different hierarchies visualize the need for real-time technologies at the field-level, where it is of most importance to keep the timing guarantees in order to produce high quality products. Even at the lowest level a wide spread of cycle times can be found [14]. Mahmud et al. [14] listed a variety of industrial control applications with cycle times as low as $100\mu s$ up to cycle times larger than $100ms$. They note that common values for process automation are situated in the range of $10-100\mu s$. Figure 2 shows different applications with various cycle times.

Cycle time	Description
$100\mu s$	*High speed I/O applications* - often managed by dedicated I/O systems, FPGAs, or DSPs
1ms	*motion control applications* - Commonly found in semiconductor production, industrial process, e.g., packaging, printing, industrial assemblies
10ms	*fast control loops application* - usually found industrial automation domains and applications, e.g., steam turbine control systems
10-100ms	Common, e.g., in process automation
>100 ms	Slow control systems

Fig. 2: Cycle Time Requirements for Various Industrial Control Applications (Table III in [14])

B. Cloud Computing

Cloud Computing itself is a relatively new technology gaining more and more presence in various areas. Rimal et al. [15] introduce a taxonomy for the cloud in order to create a common base for all work. They nicely describe different aspects such as cloud architectures, virtualization management or services provided by the cloud. The following summarizes their findings.

1) Cloud Architecture: Three architecture types are defined. A *Private cloud* is managed on the premises of the company. Thus network bandwidth between the individual nodes is known. The fact that the data is stored and handled locally is of high value for most companies where security issues are of most importance. On the other hand, a *Public Cloud* has data and computation is done in datacenters, possibly spread around the globe. This model is the most common one and has benefits such as fine grained provisioning of resources and access over the internet. The *Hybrid Cloud* is a mixture of the above mentioned models. Such an environment can consist of multiple private and public clouds, possibly connected to each other. Each architecture types has advantages and disadvantages depending on the respective area of intended use.

2) Virtualization Management: Virtualization is one of the key enablers of cloud computing. Main goal of virtualization is the division of physical resources into smaller logical partitions. Having all execution performed in such logical partitions allows reallocation at runtime which can help to adapt to changes in computational demand within the cloud. Virtualization itself, however, is dominant in embedded systems [16], [14]. Here the logical partitions are used to consolidate legacy applications on a common hardware, while still being able to keep certification for previously certified components.

3) Service Types: What kind of resources a cloud delivers depends on the service type. Common to all of them is the pay-as-you-go model, enabling the user to get just as much resources as needed without investing in hardware and maintenance costs. While finding different granularities of service type definitions in the literature, most common definitions include *Software-as-a-Service (SaaS)*, *Platform-as-a-Service (SaaS)*, and *Infrastructure-as-a-Service (IaaS)* [4], [15], and *Iaas* only delivers blank OS installations to the customer a *PaaS* provides already all environments needed for system development. Note that *Paas* is tailored to the intended use case. *SaaS* leaves the user with a ready to use service. Multi tenant applications and supporting various numbers of customers at a time are situated in this service level.

III. Cloud Computing in Automation Systems

In this section we summarize already existing work, where cloud computing and or ideas related to cloud computing have been applied in the context of factory automation. Factory automation can be decomposed into several layers, where each has different requirements. Thus we look at different parts of the automation pyramid (Figure 1) separately. We identify three main layers, enterprise and resource planning, manufacturing and high level control, and filed level. A short survey on these three layers has been done in [5].

A. Enterprise and Resource Planning

There are several work addressing the usage of cloud computing in high levels of automation. Among these work, some of them focused on the business model. For example, Xu et al. [17] investigated an intelligent factory network based on cloud manufacturing in order to transfer the business model from a traditional model to a more effective model. The key ideas are related to IT and business model, such as pay-as-you-go model, production scale up and down per demand, and flexibility in deploying and customizing the solutions.

Perez et al. [18] proposed a new paradigm of cloud manufacturing, which is called cloud agile manufacturing. In this proposal, all elements in an industrial system are available as services and fully built on Internet technology. This can provide functionalities of the automation systems for the users as services with minimum complexity. The proposed solution consists of five stages, which is shown in Figure 3.

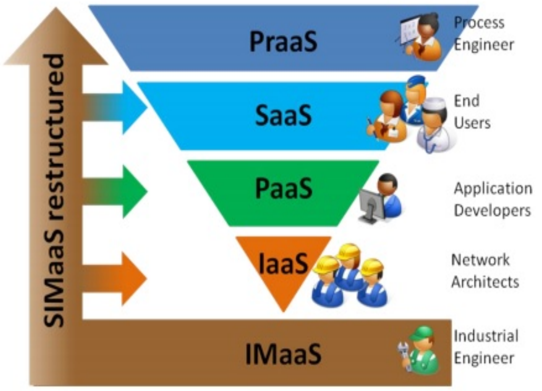

Fig. 3: Cloud Agile Manufacturing Layers [18]

In Figure 3, SaaS, PaaS and IaaS are traditional models of cloud computing with some redefining to conform to the characteristics of the new paradigm. However, the two new layers are Production-as-a-Service (PraaS) and Industrial-Machinery-as-a-Service (IMaaS). The former one is focused on the organization processes. Whilst, the latter layer is similar to IaaS where IT infrastructure is provided, however, in IMaaS the machinery is virtualized to be used as a service.

Gilbert-Iglesias et al. [19] proposed a service model to provide the industrial machinery as a service. This facilitates production process to deliver self-management and proactive management of the business logic.

B. Manufacturing and High Level Control

Manufacturing and high level control includes various different areas, each with a specific goal in mind. Such areas are Production Operations Management, Quality Operations Management, Maintenance Operations Management and Inventory Operations Management [20]. Those areas can be designed separately but for correct operation of the factory interaction is necessary. Karnouskos et al. [20] proposed the design of a service oriented cloud, fulfilling the requirements of a production management system. They proposed a Service-Oriented Architecture (SOA) approach to keep the established organizational groups of todays systems. This is important since factories are rarely built from scratch. Thus, backwards compatibility is of great importance to be able to gradually change from todays systems to future technologies.

Karnouskos et al. [21] also focused on SCADA/DCS systems. The number of monitored systems and subsystems is steadily increasing. This increases the complexity of system design and integration. The authors argue that the next generation SCADA/DCS system could be a System of Systems(SoS) exploiting the recent advantages of IT technologies. The evolution of the systems is illustrated in Figure 4. Allowing to cope with the increasing number of diverse distributed data and information.

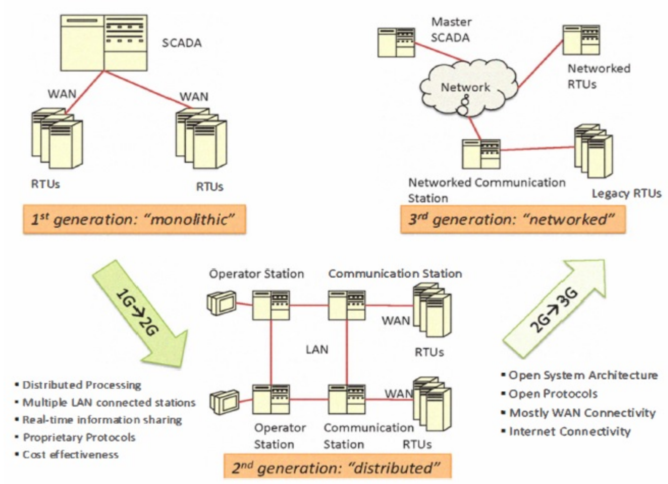

Fig. 4: SCADA Evolution [21]

In [22] the authors looked at important consumer aspects when moving a SCADA system to the cloud. The authors addressed the benefits of cloud based SCADA systems like the pay-for-use model, reduction of IT costs, scalability and easy access. Moreover, risks are outlined in detail. The three main risks identified in the paper concern security, performance and reliability. For this the authors assume the SCADA system to be hosted in a public cloud where possibly secure data needs to be transmitted over public networks. Public networks are also identified as critical for latencies since those networks are in general unpredictable with unknown bandwidth. As third risk the authors named performance. Any downtime of the production systems is expensive and might give competitors advantage. Relying on cloud providers thus assumes trust and adequate reparation payments to the company if the negotiated service qualities can not be met by the cloud provider.

SCADA systems used to control widely distributed systems, like oil or gas pipelines, are main motivation for the cloud based systems described in [23]. The connection of all devices of such a distributed system to public networks with data acquisition and control in the cloud leads to reduction in hardware and energy costs. Since SCADA applications have real-time requirements the authors proposed a task model to capture the characteristics of such tasks. In detail, their model assumes redundant copies of each task executing on heterogeneous servers. However the authors do not address the network and virtualization delays encountered in cloud based systems. Further they investigated a private cloud design tailored for SCADA systems.

In addition, Givehchi et al. [11] presented a case study for using Control-as-a-Service by taking virtualized PLCs instead of physical PLCs in a factory automation. The proposed solution is illustrated in Figure 5. Based on this proposal, PLC can be implemented as a virtual entity and its service can be delivered through the network. Note that in this proposal the cloud is a private cloud platform.

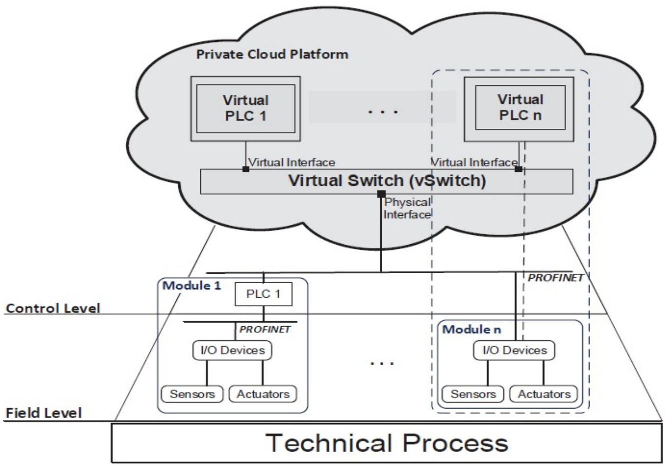

Fig. 5: Generic Cloud-based Control Approach [11]

In order to implement the virtual PLCs, authors have used VMware's vCloud suite [24]. They defined a performance metric which is called average of end-to-end delay. They compared the average end-to-end delay of using virtual PLCs and a hardware PLC and they showed that the overhead of using virtual PLCs could be higher. However, they claimed that the solution looks promising for soft real-time applications, without presenting the applicability in real industrial applications.

One of the common problems of all systems using the public network/the internet as communication medium is its unpredictability. Without having upper bounds on the communication times a successful usage in most systems with stringent timing requirements seems challenging. A possible solution is the usage of private clouds, located inside of large factories and thus allowing predictable usage. But work on enabling the usage of the internet for industrial purposes is a current toppic as well. Mainly, the Industrial Internet Consortium [1], as a newly founded organization, is working on practical as well as theoretical problems related to enabling industrial usage of the internet.

C. Field Level

Service based approaches are also interesting for the field level in factory automation. Having control loops executing in the cloud has several advantages. Sensors, actuators and fast control systems can be connected to the cloud. Ethernet or wireless based networks make an easy connection to the cloud possible [25], [26]. Thus, next generation of industrial applications can be rapidly composed since the installation overhead of control devices is not needed anymore.

[1]www.iiconsortium.org

There are several work addressing the use of cloud computing for sensor network application, which is called Sensor-Cloud. Alamri et al. [27] described several solutions regarding to the sensor cloud architectures. According to the authors, sensor-cloud collects the information from sensor networks, processes the gathered data and enables the information sharing in a big scale. Thus, users can easily access to the data in order to process, analyze and store the sensor data from different applications (i.e. different sensor networks).

The sensor-cloud architecture is depicted in Figure 6. The infrastructure provides service instance, by means of virtual sensors, to the users when they are requested. The virtual sensors act as a IT resources (i.e., storage and CPU computational resource). The sensor data can be used by the users through an interface, normally the web crawlers. The users make a request for the sensor data by selecting an appropriate service template of sensor-cloud, that is delivered automatically.

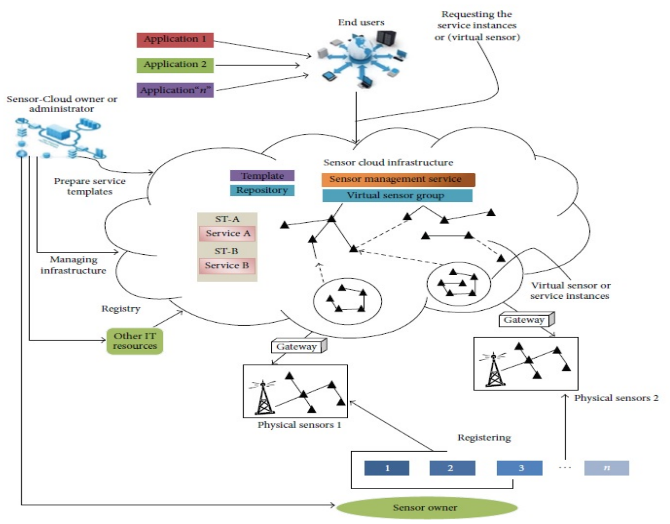

Fig. 6: Sensor-Cloud Architecture [27]

The authors of [27] described some advantages of using the sensor-cloud concept. One of the profits is scalability which the organizations can scale (add extra services) to the system without investing heavily on hardware resources. This profit is quite obvious and general in case of adopting cloud computing technology. Among other profits, the authors mentioned analysis of the data by the cloud, dynamic provisioning of increased data storage and processing power, flexibility, agility of services and quick response time. Moreover, by sharing the resources among several applications the resource optimization can be achieved.

Figure 7 illustrates the layered structure of the sensor-cloud. The authors of [27] divided the sensor-cloud structure into three layers: (i) user and application layers, (ii) Sensor-cloud and virtualization layers, and (iii) template creation and tangible sensors layers.

The first layer deals with the application which the users access to the sensor data by them. This can be assumed as a user interface of the cloud infrastructure. The second layer is helping to access the sensor data without being worried about the senors locations. Finally, the last layer helps to retrieve the data from the physical sensors.

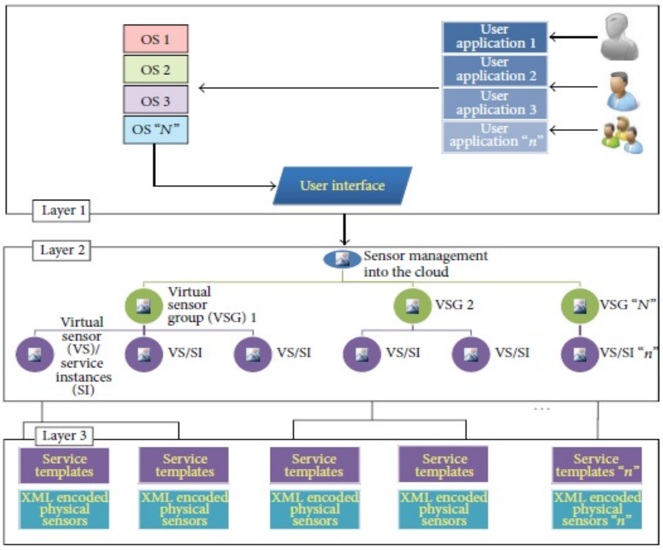

Fig. 7: Sensor-Cloud Layers Structure [27]

There exist several sensor-cloud applications which among them we can mention Nimbits [28], Pachube Platform [29], IDigi [30] and ThingSpeak [31].

IV. Open Problems

In this section we discuss open issues of using cloud computing technology in factory automations. We, again, split the open problems into three parts to be consistent with the previous section on introducing the cloud for automation systems.

A. Open Problems in Enterprise Level

According to the investigation presented in [17], there are several research outcomes from cloud manufacturing, e.g., [32] in which a Distributed Interoperable Manufacturing Platform (DIMP) has been proposed for CAD/CAM/CNC applications. However, there has been no report on development of cloud manufacturing. Therefore, several essential requirements should be taken into account in the development. For instance, fault tolerance is an important issue to have a continues operation when a failure arrives. Moreover, quality of service, which consists of availability, security and reliability, is another issue to be considered.

B. Open Problems in Manufacturing and High Level Control

As presented in Section III-B, a lot of work has been done to exploit the benefits of cloud computing in the area of Manufacturing and High Level Control. Timing requirements on this level of the automation pyramid are presented but main focus should be set on reliability and privacy.

Executing redundant copies of critical software on different servers with an agreement step before taking decisions could be a way to increase reliability and security. Also communication protocols tailored to the specific needs encountered in such scenarios with high data throughput are an open problem.

The presented timing requirements are not so stringent. Thus, research in bounding end-to-end delays of the applications is a necessary topic when using cloud computing technology in automation systems. Some works, e.g. [23], looked at the requirements of an application which is then executed in a redundant way. However the work does only focus on the placement of tasks onto individual virtual machines hence leaves space for additional work targeting the deterministic execution of virtual machines in the cloud computing context. Public networks, as used in public clouds, are non deterministic. Thus, focus on private clouds where network characteristics are well known are an interesting first step.

C. Open Problems in Field Level

The are some issues related to designing the sensor-cloud infrastructure where some of them are already researched. However, there are still some open problems to be considered for this type of cloud structure.

One of the problems is regarding the privacy and authorization. The sensor data should be available for authorized users, thus different levels of data accessing should be defined. In general, the privacy and security issues are not fully addressed in the field level cloud computing automation.

Another important issue is the real-time sensor data. There are some applications with real-time constraints, both hard and soft, where the data should be delivered on-time. The timeliness issues in the automation field level have not been thoroughly investigated in the literature.

V. Conclusion

Cloud computing, as a recent innovation in the IT community, brings new advantages and is already used on a variety of applications. The agility, the reduced development time, and the flexible payment model makes it very interesting for industrial applications as well. In this paper we gave a broad overview of the usage of cloud computing technologies in the context of factory automation. Separating the different areas based on the hierarchies of the automation pyramid the paper summarized related work in the layers of Enterprise and Resource Planning, Manufacturing and High Level Control, and the Field Level. This separation is needed since all layers deal with different requirements depending on the intended usage. For example, timing requirements are strict and have short periods at lower levels but relax more and more when we ascend the automation pyramid, giving space for other important requirements on those levels.

Since not many work have addressed the concrete needs of factory automation systems, we addressed a range of possible work to contribute to the area and make the practical use of cloud based systems possible. Main point for future work is the lack of real-time support on the communication links, as well as in the models and assumptions of higher levels of the automation pyramid.

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