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Extended study of network capability for cloud based control systems

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ABSTRACT

Current control systems are limited from a technical viewpoint in areas such as scalability, start-up and reconfiguration time and computational complexity for algorithms. These limitations call for a new concept for control systems to address current and future requirements. It has been suggested that the physical location of the control system be moved from that of the machine to a cloud, i.e. control system as a service (CSaaS). In this way, the control system becomes scalable and can handle highly complex computational tasks while keeping the process know-hows. Utilizing capabilities of modern Wide Area Network (WAN) and Local Area Network (LAN) the control system can be connected with the rest of the machine, e.g. drives, sensors, devices and HMI. This approach, however, presents new challenges, i.e. the requirement for integration of network, cloud computing and control system expertize. This paper will focus on the requirements of the communication for a cloud based control system.

1. Introduction

> "Intelligence is the ability to adapt to change." – Stephen Hawking

This quote from Stephen Hawking is also valid for production systems today. Only intelligent production systems can meet the requirements of a flexible production of the 21st century with increasing demand for versatility and scalability. Intelligent production systems can be developed only if the control system is intelligent, while current machine controls are not. Being limited in areas like e.g. reconfiguration ability [1], security [2] and computational power [3], the machine control demands for a radically new concept. In recent years, cloud computing have been dramatically changing enterprises and industries in the way of organizing business. Cloud manufacturing adopts the concept of cloud computing, i.e. virtualized manufacturing resources are distributed through Internet as services, and encourages resource sharing and collaboration among medium and small sized enterprises especially [4]. Researcher in cloud manufacturing area mainly focus on the system architecture [5], service management [6], and enabling technologies of cloud manufacturing, such as virtualization of manufacturing resource [7] and service oriented technology [8].

The chosen approach of the project of the joined research between the Institute for Control Engineering of Machine Tools (ISW), University of Stuttgart, Germany, and the Department of Mechanical Engineering, University of Auckland, New Zealand, is to provide a control system as a service (CSaaS) from a cloud environment. In this way, the control system becomes scalable and can handle highly complex computational tasks while retaining the process know-hows. Utilizing capabilities of modern Wide Area Network (WAN) and Local Area Network (LAN) the control system can be connected with the rest of the machine, e.g. drives, sensors, devices and HMI. For the owner of the machine, there is no difference to a conventional machine control. This approach, however, presents new challenges, i.e. requirements for integration of network, cloud computing and control system expertize.

Networked Control System (NCS) is the control system in which the components including controller, sensors, actuators and other system components exchange the information using a shared media or network [9]. For several decades researchers investigated the influence of network imperfections including delay and dropout to the system performance e.g. the scalability [10], stability [11], and quality of control (QoC) [12]. The system performance is also application dependent, for example, the sampling rate [9] and whether the sampling is time-varying or constant [13] will influence the system performance. Among industrial control networks, realtime Ethernet (RTE) gains the popularity in manufacturing area because Ethernet is faster, more capable of transmitting large quantity of data and cheaper in hardware [14]. Apart from that, it still maintains the possibility of migrating from the home and office Ethernet to RTE, using standard hardware/software components and permitting coexistence of Ethernet and RTE on the same cable [15]. Three realtime classes are identified: soft

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real-time with scalable cycle time used by shop-floor monitoring, hard realtime with cycle time 1–10 ms used by process control and isochronous realtime with cycle time 250 μs to 1 ms and jitter < 1 μs used by motion control [16]. The Ethernet is based on the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) mechanism which cannot guarantee time-deterministic transmission [17]. To deal with that issue, many adopted solutions involve modifications to the Ethernet, which could be categorized into three different approaches. The first one modifies the top layer rather than the TCP/UDP/IP protocols and be called “on top of TCP/IP”. Modbus/TCP, EtherNet/IP, P-Net and Vnet/IP belong to that category. The second one bypasses the TCP/UDP/IP protocols (“on top of Ethernet”). Ethernet Powerlink (EPL), Time-Critical Control Network (TCnet), Ethernet for Plant Automation (EPA) and PROFINET CBA are typical examples. The last one modifies the Ethernet mechanism and infrastructure to reach real-time performance (modified Ethernet), which includes SERCOS III, EtherCAT and PROFINET IO [15]. However, in the cloud based control scenario the communication between the cloud and the machine goes through different Internet service providers' Wide Area Networks (WANs) which may use different technologies e.g. fiber, xDSL, coaxial cable, which are in different architecture in Layer 1 and Layer 2 according to Open Systems Interconnection (OSI) model. At the boundary of WANs and Local Area Networks (LANs), hubs, switches, routers and firewalls are implemented. To make possible the data's being transmitted through Internet, no modification to Layers 1–3 in OSI model is performed [18]. With the first solution mentioned above the communication is possible over the Internet, however, it may requires the exclusive use of the network. For better realtime performance, it may also utilize IEEE1588 [19] protocol whose packets cannot travel through ordinary routers. The second solution modifies the TCP/UDP/IP protocols, which is hardly possible to go through firewalls. The last solution relies on the modified Ethernet hardware. Even general Ethernet hardware and software components cannot meet its specification.

Providing control system as a service over networks creates additional challenges resulting from the nature of the IT infrastructure. Communication errors could happen on a communication route and have to be considered by a communication protocol [20]. The errors “repetition”, “loss”, “insertion”, “wrong sequence”, “falsification” and “delay” are also relevant for CSaaS and have to be detected and resolved by a communication protocol or even by the cloud machine control.

As a first test to CSaaS a communication analysis has been done between two servers located in Germany. The results, which support the idea of a CSaaS, were presented on the SPS/IPC/Drives congress in Nuremberg, 2013. However, the very short communication path and the limited period (only 1–2 h) were not able to provide sufficient data to identify the challenges of WAN towards CSaaS.

This paper presents an opportunity analysis for the communication of control data between a machine and cloud-based control. The opportunity analysis is based on two scenarios. For the first scenario, the cloud-based control is located in Stuttgart, Germany whereas the “machine” is located in Auckland, New Zealand. In the second scenario, the cloud-based control is also located in Stuttgart, Germany but the “machine” has been moved to a Google cloud center located in Europe.

In the first section of the paper, requirements of the communication between cloud and machine based on two use cases are defined. Based on the use cases, a network test setup is described in the second section of the paper, which locates the control system's communication module in Stuttgart and the dummy communication module of a simulated machine in Auckland or at the Google cloud Europe. The test setup is expanded by a monitoring solution to analyze the network behavior. In the third section of this paper, the communication monitoring results will be discussed with respect to parameters, which have a big impact on the production process. As a final section, strategies will be presented for both use cases that could resolve some of the communication challenges of Section 3. The paper ends with a conclusion whether a cloud-based machine control for machines could be possible.

2. Use cases and communication requirements

As a first step towards a control system as a service, a general understanding of the transferred data between control system and machine has to be developed. It is important to know what type and amount of data is transferred in which cycle time. Further knowledge is needed about the impact of the data on the process results and if the data is part of a control loop. This analysis has been done based on two use cases. One use case is based on a five-axis milling machine located in Stuttgart, the other one is based on a three-axis milling machine in Auckland.

2.1. Use case 1: five-axis milling machine

For the first use case, an Exeron HSC 5-axis milling machine is used. For the Exeron HSC 600 three types of data streams could be identified which have always a two-way communication with the control system:

- Data that is exchanged between spindle/axis drives and the control system. This data includes drive control and status word, setpoint and actual position. The origin and destination of these data is the computerized numerical control (CNC).
- Data that is exchanged between the machine control and I/O terminals. This data is linked to the programmable logic controller (PLC) where e.g., pumps are controlled and information of sensors is evaluated for plausibility checks [21].
- The third data stream is originating and ending in the human machine interface (HMI). Actions taken by the machine user have to be transferred to the machine control (e.g. start NC program) and feedback values (e.g. current line of executed NC program and axis position) have to be transmitted for visualization.

Table 1 shows the data streams corresponding to the amount of data and cycle time. The direction is relative to the machine control. These values are the ones configured by the vendor of the machine.

A closer look at the transferred data, especially for the I/O terminals, identifies that a cycle time of 1 ms is not necessarily required. The internal bus of the I/O module and the used clamp can expand the reaction time dramatically.

As a second step, control loops, which are depending on status values resulting from the machine in the machine control, have to be identified. For the Exeron HSC 600 machine the most critical control loops are resulting from the axis and the CNC system. The CNC is performing the following:

- Check if the actual position is within a monitoring window to the commanded position. If this is not the case, an error is set. This behavior results in the requirement to either deactivate or increase the monitoring window or do the comparison within a short cycle time, for example by shifting this checking procedure closer to the machine.
- Check if changes to the drive control are executed according to the expectations of the CNC and correctly reported by the drive over the drive status. A possible solution would either be a

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