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Design of a machine tool control system for function reconfiguration and reuse in network environment

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ABSTRACT

Computer numerical control (CNC) systems are becoming multi-functional as the requirements for manufacturing quality, efficiency and product diversity are becoming more rigorous. The reconfigurability and scalability property of CNC are important for reducing manufacturing costs and functional redundancy and shortening manufacturing time. However, in current CNC systems, functions are closely coupled in a real-time operation environment. This has been a main obstacle for implementing a scalable and reconfigurable CNC system. This paper proposes a new type of CNC system named invisible numerical control (INC) system to simplify CNC architecture and improve CNC architecture reconfigurability and function reusability. INC system consists of three sub-systems, namely project center, motor controller and mobile terminal. The functions of the sub-systems are machine control instructions generation, execution of machine control instructions and process control respectively. The sub-systems are organized in loosely coupled manner. This is enabled by current computer/information resources and technologies such as high speed data transmission, large capacity and high speed storage, standard communication protocols and compiled operation of machining programs. By configuring different functions in project center, it can generates uniform machine control instructions for multiple and different types of machine tools. Therefore, reconfigurability and function reusability are achieved. This paper illustrates the functions, architecture and information model of INC and builds an INC prototype. Case studies show that by using current off-the-shelf hardware, INC can be implemented to undertake different manufacturing tasks.

1. Introduction

CNC system lies at the bottom layer of manufacturing system. As computer/information technologies are developing rapidly, it is important to optimize the architecture and operation mechanism of CNC to achieve higher machining quality and efficiency and lower machining costs.

The development of CNC is closely related to the development of computer/information technologies and software development technology. Similar with the development of computers, early numerical controllers went through stages of electron tubes, transistors and small scale integrated circuits. These numerical controllers are named hardwired numerical controllers (HNC). Numerical control systems significantly improved the manufacturing quality and efficiency, however, the architecture was complex and the functionality was simple. It was difficult to program for the numerical controllers. Since large scale integrated circuits were invented in 1970s, numerical controllers became computerized [1]. Computerized numerical controllers are more programmable and flexible, which made flexible manufacturing systems (FMS) practical. The computers and peripherals of CNC at early stage are dedicatedly designed. It is difficult to reconfigure the controllers to meet specific requirements. Since 1990s, personal computers (PC) were adopted as the platform of CNC systems. Different from former CNC system platforms, PCs have standard hardware architecture, communication interfaces and uniform operating systems. Open architecture controllers (OPC) are organized in modular manner so that functions are interchangeable. By using open interfaces, users can integrate user-specific applications into the system [2]. With OPC as key enabling technology, manufacturing systems become reconfigurable [3]. Functions are configured only when needed. Therefore, manufacturing costs and system ramp-up time are reduced.

Currently there are mainly three kinds of OAC architectures, namely PC embedded in NC, PC plus motion control card and PC with real-time operating systems (RTOS) [4]. In "PC embedded in NC" architecture,

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PC serves as human-machine interface (HMI), while real-time interpolation and motion control functions are undertaken by stand-alone NC kernel. In “PC plus motion control card” architecture, NC functions are still undertaken by NC kernel which is plugged in PC through standard interface such as PCI. In the above two kinds of CNC architectures, openness is limited since NC kernel is vendor specific. In “PC with RTOS” architecture, all the control functions are executed by PC and no other numerical control platforms are needed. PC communicates with servo drives through field-bus or Industrial Ethernet [5–7]. Because PC is responsible for real-time interpolation and position control algorithms, a real-time operating system is needed to guarantee exact timing for real-time tasks. Since CNC functions are executed by PC software, this type of controller is called “soft-CNC”. Though soft-CNC has enough openness theoretically, it is still difficult to reconfigure CNC controllers and reuse the function modules. Core functions are based on the application program interfaces (API) of real-time operating systems. These functions must be carefully designed in order to not deteriorate real-time performance of the controller [8].

With more hardware/software resources as enabler, more functions are integrated in CNC controllers. Traditionally CNC controllers read G-code as input. G-code mainly contains information of tool path trajectory, feed command and input/output (IO) functions, which are not sufficient for multiple functions and cannot serve as bi-directional information flow between CNC controllers and high-level systems such as CAD/CAM [9]. Therefore, STEP-NC has been proposed as object-oriented machining task description program [10,11]. Using object-oriented approach, STEP-NC programs contain information of machining features, machine tools, machining strategy, tool paths, etc. [12]. With the above high level information, CNC controllers have more decision making ability and intelligence, such as modifying machining strategy or machining tool paths. Meanwhile, modifications can be fed back to CAD/CAM systems [13]. STEP-NC increases the interoperability of CNC controllers and fills the gap between CNC and CAD/CAM. Functions originally belong to CAD/CAM systems are integrated in CNC systems, such as manufacturing feature recognition and tool path generation. STEP-compliant CNC system is more than just a machine tool controller, but rather an integrated manufacturing data processing platform.

With the development of information and communication technologies, manufacturing systems are stepping into a new stage which is widely known as Industry 4.0. Initiated by Germany, Industry 4.0 describes the fourth industrial revolution enabled by cyber-physical systems (CPS), internet of things (IOT) and services [14]. In the realm of Industry 4.0, resources involved in value-adding process such as humans, objects and systems are networked to create smart factories [15,16]. In smart factories, manufacturing systems can communicate with each other and response rapidly to different requirements. By using CPS and IOT technologies, manufacturing systems achieve intelligence such as self-awareness, self-prediction and self-reconfiguration [17].

As the key element of manufacturing systems, machine tools also need to make changes to keep pace with upcoming Industry 4.0. Xu [18] named machine tools in context of Industry 4.0 Machine Tool 4.0. By connecting machine tools into manufacturing networks as a cyber-physical production system, machine tools can be smarter, more adaptive and more autonomous. With smart machine tools such as Machine Tool 4.0, smart factories become distributed and collaborative. The business logic of machine tools can be moved into cloud-based applications and provide smart products and services [19].

In order to achieve smart machine tools, the controllers of machine tools should be well-connected and interoperable with the aid of network-based or cloud-based system [20–22]. In network-based or cloud-based paradigms, CNC controllers are not merely stand-alone assembly of hardware and software. The reconfigurability and scalability of CNC should be considered in a distributed environment instead of local shop floor. Functions of CNC systems should be available to multiple machine tools in plug-and-play manner. It is worth mentioning that research on remote operation and monitoring of machine tools arose earlier than the research on Industry 4.0. Ong et al. [23] and Hanwu and Yueming [24] developed network-based virtual CNC systems respectively. Users can virtually operate machine tools via web browser. Wang et al. [25], Torrisi and Oliveira [26] and Adamson et al. [27] developed remote CNC machine tool control platforms. Meanwhile, real-time monitoring of machining is realized. Liu et al. [28] designed a cyber-physical manufacturing cloud architecture. Local machines receive machine operation requests from the cloud and feedback status information. In the above researches, a local CNC controller is still needed to parse machining programs and generate motion instructions for servo drives. Verl et al. [29] proposed a framework of cloud-based machine control methodology. The control functions are moved up to the cloud, while the framework needs a cloud-based real-time operating system to handle real-time tasks. Schlechtendahl et al. [30] evaluated TCP/IP and UDP protocols performance in the framework that control functions are moved up to the cloud without local CNC systems. The results showed that current TCP/IP and UDP protocols cannot meet real-time performance and quality of service that real-time cloud-based CNC system execution required.

Current manufacturing paradigms such as Industry 4.0 are aiming at more reconfigurability, scalability and function reusability via network environment to shorten manufacturing time, reduce costs and increase system adaptability. However, while the upper layers of manufacturing system are becoming cloud-based and service-oriented, CNC systems are still bound to local machines. The main reason why current CNC systems cannot operate in remote platforms is the closely-coupled architecture of CNC systems. Key functions such as machining program parsing and tool path interpolation are executed in compact real-time platforms. In such platforms CNC function algorithms have to be carefully designed to meet real-time requirement. These functions can only serve corresponding local machine. While more functions are integrated in current CNC architecture, function reusability becomes low.

The object of this pater is to present a new CNC architecture that fits current network operation environment. The authors name the proposed architecture invisible numerical control (INC). With fundamental technologies advancements such as rapidly increasing Ethernet throughput and mass storage capacity, INC system is organized in loosely coupled manner by using object-oriented programming (OOP) and service-oriented architecture (SOA) technique. In INC architecture, machine control instructions are generated in non-real-time environment. Therefore, INC can operate remotely rather than configuring CNC system locally. This feature is very important to achieve high reconfigurability, scalability and function reusability.

The rest of this paper is organized as follows: Section 2 describes the concept of INC. Section 3 designs INC system architecture. In Section 4 a prototype system is built and in Section 5 experiments illustrates the property of INC. The authors' conclusions are stated in Section 6.

2. Concept of INC

2.1. Overall architecture of INC

Invisible numerical control (INC) is a network-based and distributed machine tool numerically control paradigm. By adopting loosely-coupled architectures and defining communication interface among function modules, INC achieves high degree of reconfigurability, scalability and function reusability. INC system interacts with machine tools in plug-and-play manner. The term “invisible” implies that machine tool motion command generation related functions are all implemented in network environment and are invisible to local users.

The overall architecture of INC is shown in Fig. 1. It has three subsystems, namely project center, motor controller and mobile terminal. Project center is a remote manufacturing management and machining instruction generation unit. It is the aggregation of CNC related