Robotics and Computer-Integrated Manufacturing 27 (2011) 963–976

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Design methodology for smart actuator services for machine tool and machining control and monitoring

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ARTICLE INFO

Article history:
Received 1 June 2010
Received in revised form
18 February 2011
Accepted 14 March 2011
Available online 20 April 2011

Keywords:
Machine tool
Machining
Control
Monitoring
Smart actuator
Multi-agent system

ABSTRACT

This paper presents a methodology to design the services of smart actuators for machine tools. The smart actuators aim at replacing the traditional drives (spindles and feed-drives) and enable to add data processing abilities to implement monitoring and control tasks. Their data processing abilities are also exploited in order to create a new decision level at the machine level. The aim of this decision level is to react to disturbances that the monitoring tasks detect. The cooperation between the computational objects (the smart spindle, the smart feed-drives and the CNC unit) enables to carry out functions for accommodating or adapting to the disturbances. This leads to the extension of the notion of smart actuator with the notion of agent. In order to implement the services of the smart drives, a general design is presented describing the services as well as the behavior of the smart drive according to the object oriented approach. Requirements about the CNC unit are detailed. Eventually, an implementation of the smart drive services that involves a virtual lathe and a virtual turning operation is described. This description is part of the design methodology. Experimental results obtained thanks to the virtual machine are then presented.

1. Introduction

In the manufacturing context, machine tools can be considered as particular goods. Indeed, they are the products of firms that sell them to other firms for which those machines become productive resources. That is why, on one hand, they have to be designed and manufactured in order to be as customizable as possible to respond rapidly to the customers' demands and, on the other hand, they have to be productive with minimum downtime, flexible and reactive while they are operating in the customers' workshops.

The flexibility has been improved thanks to programmable numerically controlled machine tools. The ability to be programmed has contributed to increase the number of types of processes that can be achieved by a machine tool and to increase the geometry complexity of the machined parts.

The productivity, in terms of rapidity, has been improved thanks to the developments of high-speed machining processes. The machine tools that are able to achieve those processes have specific mechanical structures. New functions with adjustable parameters are implemented in their control systems in order to calculate tool trajectories that reduce the effects of undesirable but predictable phenomena that can appear during machining [1]. High speed machining also requires new performances for the computation of the tool paths [2]. The enhancement of productivity can also be obtained by reducing downtime. This reduction is the main goal of OSA-CBM (Open System Architecture-Condition Based Maintenance) project by providing to computerized maintenance and production management systems health assessments of production equipments that combine data on their current health as well as their future health from diagnostic and prognostic treatments [3,4].

Machine tool manufacturers can proposed customized machine tools to their clients by applying modular design to their products. Indeed, the modularity of the structural design of machine tools enables to achieve the combinations of processes expected by the customers and independent controls of spindles and axes motions. The modularity is also a major consideration for the design of their control and monitoring systems for which expected features are scalability, interoperability and portability [5,6]. Object-oriented modeling and programming languages ease the generation of software for such systems because they enable the encapsulation, the specialization, the reuse of functionalities and polymorphism [7,8].

The reactivity is the ability to adapt rapidly to changing environment and it consists in managing freedom degrees of flexible systems. Although the CNC (Computer Numerical Control) machine tools are flexible at the workshop level because of their ability to be programmed, the machine tools become less flexible and therefore not really reactive when the work-piece program is running. Indeed, their monitoring functions often lead to stop the machining operations if an abnormal behavior is detected in order to avoid more damages. Adaptive controls are solutions to

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doi:10.1016/j.rcim.2011.03.004

counter the changes of the machining process parameters such as tool wear, depth of cut, vibrations, etc., but they are often very dedicated. Indeed they can keep the cutting force constant or aim at reducing vibrations [9,10].

In order to ease the integration of new functionalities, open and/or modular architectures of CNC have been developed [5,11,12] as well as integration frameworks and languages for distributed computer systems [13]. The development of open architectures of CNC is also guided by requirements in terms of agile manufacturing that lead to the integration of the CNCs of the machine tools to the CAD-CAM systems [14,15] and even in terms of remote manufacturing [16]. Frankowiak et al. [17] analyze in their review paper on microcontroller-based machine and process monitoring several eligible architectures. Nevertheless, those architectures exploit the computational abilities of the CNCs. Indeed, the added functions are implemented in the CNC or in, other platforms that perform completely or partially the added functions that communicate their results to the CNCs. In such architectures, the CNCs are still the lowest decision centers of the manufacturing systems. Wang [14] proposed an integrated design-to-control holonic manufacturing systems where intelligent sensors/actuators are mentioned. Even if the use of smart or intelligent sensors/actuators enables to add a new decision level closer to the process thanks to their computational abilities, they are quite never considered although this contributes to the improvement of the reactivity of the manufacturing system [18].

The main goal of this paper is to propose a design methodology of smart drive services for CNC machines to enhance, for the machine manufacturers, the modularity and, for the machine users, the productivity and the reactivity. The proposed design methodology exploits the object oriented approach and joins the smart actuator concept, which is firstly presented as well as its underlying functionalities. Although the smart actuators enable to improve performances that are listed in this paper, they do not contribute to the improvement of reactivity at machine level. This improvement requires the capacity of managing freedom degrees at the machine level. The multi-agent system approach enables such a management aiming at predefined objectives that may vary according to the requirements of the machining processes. That is why the proposed design extends the smart actuator with the notion of agent, which also satisfies the need of modularity. The paper then presents the description of the services of a smart drive, the interactions between the smart drives and the CNC unit and underlying requirements for the CNC unit. The last part is dedicated to the presentation of an implementation that is also the methodology guidelines. The aim of this implementation is to controls and to monitoring a virtual CNC lathe and a virtual turning process. The treatments of the proposed services are detailed for this application and results obtained thanks to the virtual machine and process are given.

2. Smart actuator concept

The smart or intelligent sensor and actuator concepts were defined in the 1980s. They address the lack of reliability in complex systems inherent to the numerous sensors and actuators needed for their control and monitoring. The proposal of this concept consists in adding information processing and bi-directional communication abilities to the main service functions of sensors and actuators [19,20]. Of course, the concept also took advantage of the emergence of field buses (CAN, FIP, Profibus, etc.). The smart instruments also contribute to the distribution of data processes and of data bases closer to the physical process. That decentralization improves the modularity of the systems. Indeed, it enables to update or to replace local devices with only minor actions on some other components (e.g. to set up a new device in the bus manager):

The information processing ability is mainly used to implement functions dealing with the following:

- Measuring to transform physical values into computable data.
- Elaborating reliable data as close as possible to the real situation to send them to the other devices of the system.
- Monitoring and diagnosing to provide data dealing with the health status of the smart actuator and of the part of the physical process on which it operates.
- Acting safely to make decision about actions to do those correspond to the real situation and to predefined objectives.
- Communicating to send data, like health status, to other devices of the system and to get data, like objectives, from other devices of the system.
- Managing the internal application and data base.

Those functions provide various services. Elaborating reliable data mainly deals with data validation that improves the metrologic quality of measurements. Monitoring and diagnosing provide data about the health status of the actuator; those data become decision supports for various purposes:

- The maintenance management to plan, to prepare and to do the maintenance actions.
- The production management to plan production knowing the availability of the production resource, and to act safely.

'Acting safely' reinforces the system safety and reliability by adapting to the situations observed by monitoring and diagnosing functions whom information are processed from validated measurements. 'Communicating' enable the necessary data exchange between the various devices of the productive resource [21].

In most cases, the studies carried out in the field of smart actuators are led to develop actuators dedicated to the achievement of a specific function of a given kind of system [22–24]. However, the use of smart actuators is not entirely satisfying. It is especially the case for the reaction to disturbances mainly because their behaviors are strongly predetermined like in the particular case of adaptation techniques that aim at keeping constant the cutting forces [9,10]. Those adaptations are specialized and do not entirely match flexibility requirements.

3. Adding agent abilities to smart actuators

In order to improve the flexibility of adaptation functions, freedom degrees must be created at the machine level. The management of those freedom degrees requires decision-making abilities carried out by the smart actuator. In that way, those smart actuators are able to react rapidly when they detect a disturbance by making the appropriate decision according to defined goals and boundaries. The detection of disturbances or the detection of situations that do not lead to the satisfaction of the defined goals require cooperation between the smart actuators because they all contribute to the achievement of the process, as well as they require cooperation between them and the CNC unit, which can be considered as a supervisor [18].

Smart actuators with decision-making abilities can be considered as agents according to the definition of a computational agent given by Jennings and Wooldridge [25] where an agent is defined as a self-contained problem-solving computational entity able, at least, to perform most of its problem-solving tasks, to interact with its environment, to perceive its environment and to respond within a given time, to take initiatives when it is