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Research on multi-robot open architecture of an intelligent CNC system based on parameter-driven technology

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ABSTRACT

This paper presents a multi-robot open architecture of an intelligent computer numerical control (CNC) system based on parameter-driven technology that has been developed for flexible and high-efficiency manipulation. An open architecture control system capable of distributed processing of decision-making and extraction of task information provides a premise for intelligent control and flexible operation. Intelligent detection with database feedback based on real-time assignment of tasks is proposed to achieve dynamic modification of the processing trajectory. In the context of flexible task control, a multi-robot architecture with collision-free path planning and a novel programming approach based on parameter-driven technology are developed. The proposed CNC system has been successfully implemented and demonstrated on an H-beam steel-cutting task that requires flexible and accurate machining.

1. Introduction

The diversification of the machining process and the complexity of the geometric configuration of a workpiece endow more openness and flexibility to new generation computer numerical control (CNC) systems. Open CNC architecture with more merits, such as interoperability, portability, interchangeability, extendibility, etc has been proposed in recent years to adapt to the agility required in implementing various manufacturing processes [1]. Open architecture control (OAC) is a concept derived from the flexibility requirement based on computer integrated technology. Some hardware reconfiguration and communication, as well as advanced numerical control (NC) programming technology, are involved in the new generation development of the CNC system [2]. Some new open architectures, such as the open system environment control (OSEC) in Japan, the open system architecture for controls within an automation system (OSACA) in Europe, and the open modular architecture control (OMAC) in the USA [3], employ modularized functions and standardized communication infrastructure for transparent data exchange and plug-and-play adaptation. However, incompatibility between hardware and software architecture from different vendors, as well as high integration costs, hinder the application of such new technology in the conventional CNC systems.

Machine programming systems using G&M code to denote related machine motions are still considered as bespoke approaches and islands of information with little or no ability to seamlessly transfer information between different systems. To eliminate problems resulting from information exchange along the CNC manufacturing chain from design to production, the STEP-NC data model [4] and the NC program processor (NCPP) structure with separated NC specification dictionary (NCSD) and a processing engine [5] are proposed to ease the CNC system's adaptation to a new NC program using G&M code to translate motion information. This is imperative so that various systems used by different components of the supply chain are able to exchange information reliably and rapidly, regardless of their make and models [6,7]. However, traditional G&M code is sometimes invalid or at least inconvenient for certain machining processes. For example, in the profile steel-cutting task, the workblank is a finished hot-rolled steel with a specified shape and geometric dimension holding some errors of configuration, whereas the machining process is relatively fixed. In such task, conventional CNC systems using computer-aided manufacturing (CAM) systems to generate NC codes can be viewed as ill-posed solutions, where modification of exact path parameters is more essential than the entire path planning generation. A novel representation approach of the machining path based on parameter-driven technology facilitating programming through step by step parameter selection is proposed in the remainder of this paper. Fig. 1 illustrates an H-beam steel-cutting task, including two side flanges and one web plate process for fulfilling the welding requirements. The path of the cutting process is not

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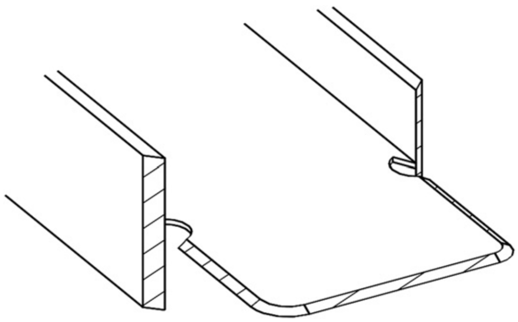

Fig. 1. Illustration of process of H-beam steel.

complicated, but demands some keen points for accurate parameter information.

Nowadays, more than the agility of programming and the interchangeability of hardware [8], intelligent manufacturing systems (IMS) with high machining accuracy and efficiency are the goals of industrial manufacturing processes in OAC systems. To satisfy high-speed and high-precision CNC machining of complex shapes, some methods, such as polynomial technology [9] and spline interpolation [10], have been proposed by the related kinematics transformation module. However, intelligent monitoring and real-time control are crucial components of IMS and are indispensable to achieve accurate tracking and rapid response. Machining process monitoring with real-time control is a core concept on which to build a new generation of flexible intelligent CNC machines. Unfortunately, direct and in-process measurements are not generally possible because of the aggressive environment in the machining zone surroundings [11]. Parameter optimization through self-learning is introduced as the main research trend in process monitoring and control strategies toward an intelligent manufacturing system. Integrating intelligent detection of the workpiece for the execution of sensor-based feedback and real-time implementation of various control tasks is a challenge to traditional CNC systems. In the H-beam steel-cutting task, a novel structured light detection (SLD) method based on machine vision is utilized to detect the geometric errors used to compensate for the actual machining path. In addition, an open modularized platform based on real-time property analysis is built to implement real-time multi-task processing.

As a result of their large effective workspace and suitability for multiple applications, more robot systems are chosen for some machining processes over conventional CNC machines [12–14]. To our regret, industrial robotic systems are designed to realize repetitive tasks with lower accuracy, from 0.03 to 0.1 mm of repeatability because of their low inherent stiffness from the cantilever design of links [12]. Matsuoka et al. [13] indicated that machining forces acting on a robot's end-effector of robot could result in high bending moments in the joints, which could generate excessive tool-tip deflection, vibration, and poor machined-part accuracy. New approaches, such as the optimal distribution of actuator compliance [14] and the application of novel machining tools with stronger stiffness, have been proposed to solve the above problems. Huang and Lin [15] indicated that there are advantages in such an application from a multi-robot point of view, such as more machining configuration, higher efficiency, and greater reliability, compared with single-robot machining. However, multi-robot machining path planning is more complicated because of the consideration of avoiding collisions between robots or between robots and workpieces. In particular, the multi-robot technology is more suitable to the three-dimensional processing of H-beam steel without any contacts between end-effectors and the workpiece. Of course, intelligent experience-based path planning by means of detection information feedback is essential to realize a collision-free multi-robot system.

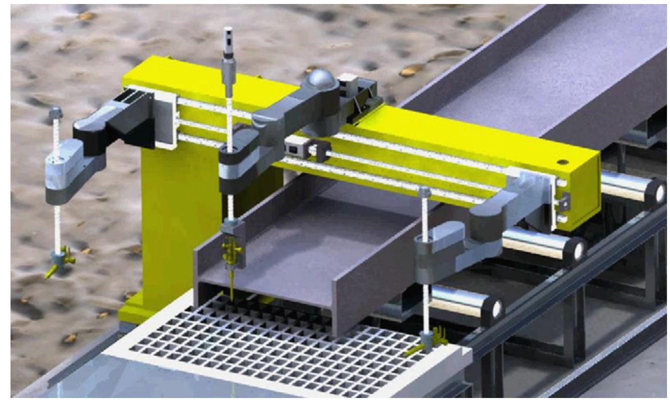

Fig. 2. Virtual model of multi-robot open CNC system.

In this paper, a multi-robot open architecture of intelligent CNC system based on parameter-driven technology is introduced. This may improve the performance of CNC machines as part of an intelligent mechatronic system. The multi-level real-time analysis of control tasks is proposed to overcome the issues of wasted system resources and fulfill the diverse requirements of different real-time tasks. The parameter-driven technology that substitutes traditional NC-code programming can facilitate the programming process efficiently and minimize mistakes. Intelligent path planning with sensory feedback as well as experience-based design is utilized to execute decision making. Multi-robot technology offers synchronous machining under different working procedures, thereby, obtaining high working efficiency. As shown in Fig. 2, a novel multi-robot open architecture CNC system has been designed and prototyped for this H-beam steel-cutting application based on the modularized control concept, where a system software with parameter-driven technology is developed under C++ environment in the Windows XP system. A related experimental study has been carried out to validate this new CNC system.

The remainder of the paper is organized as follows. Section 2 provides a hierarchical architecture in the function levels of an OAC system based on the multi-robot technology. Section 3 presents an intelligent task control scheme with real-time task assignment and database information feedback based on the SLD method. Multi-robot collision-free path planning is addressed in Section 4. Section 5 introduces how to execute process programming with parameter-driven technology. Section 6 presents the experimental results and Section 7 concludes the paper.

2. Hierarchical architecture

An open hierarchical architecture design scenario for system update and software redevelopment is conveniently adopted in the proposed system. The system is designed to allow the integration of new processing units of hardware and software modules using hierarchical control architecture, which is necessary for flexible manufacturing. Open architecture of intelligent CNC systems should possess some of these major features [16]:

- *Modularized design*. Implementation of new functions when needed would be a desirable convenience in a flexible control system. Modularized design allows some local changes with new function modules without altering the original modules. Higher priority of high-level modules used for intelligent path planning is more favorable to system optimization and reliability compared with lower priority of field-level modules for hardware management.