A new numerical control system for grinding complex profiles

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Abstract

This paper developed a novel numerical control system for digital profile grinding. The design methodology for a machine vision-oriented profile grinding numerical control system was proposed. The hardware and software structures were constructed. The CNC multithreading mechanism was analyzed. The fusion of numerical control with image processing and the machining error compensation based on the virtual axis were discussed. The experiments were conducted to verify the feasibility of the trajectory control and machine vision-based error compensation. The results can also offer references for another numerical control system with both requirements of path control and imaging processing.

Keywords: Grinding; Numerical control; System; Imaging processing

I. INTRODUCTION

With the rapid development of manufacturing industry, different kinds of parts with complex profile are in increasing demand each year. Optical enlargement based profile grinding is frequently used as a precision machining method in order to meet the processing requirements of curve parts. However, the traditional optical profile grinding machine is limited in precision and reliability, since the machining errors are manually vision detected and compensated. In this study, machine vision and image processing technologies have been introduced to optical profile grinding machine for replacing human visual perception and promoting the machining performance. Meanwhile, new open numerical control technology should be developed to realize the integration of machine vision with numerical controller.

The research of open architecture numerical control system has gained comprehensive attentions in the recent years. D. Yu et al. [1] designed an open CNC system based on component technologies which included HMI, task controller component, PLC, motion controller component and Fieldbus driver component. XU Xiaoming et al. [2] presented an open CNC system based on modularization construction and designed a software using a concentric rings structure, which proved to be highly integrated with low coupling characteristic. L. Zhou et al. [3] provided a new architecture of open CNC system based on compiling mode which accomplished the compilation and interpolation task in PC system. Yusri Yusof and Kamran Latif [4] presented a new method for open-CNC development based on the PC, motion control card, universal motion interface, LabVIEW and windows environments. T.-L. Nguyen et al. [5] and [6] have studied the vibration that occurs during the external cylindrical grinding and have optimized the 9CrSi and W18Cr4V steel grinding process multiple objectives to increase productivity and quality of the product and study in force when machining materials of different hardness.[7]

To promote the flexibility and simplify the hardware connection of open architecture CNC systems, Fieldbus has been used widely for data transmission. Y. Haibo et al. [8] presented the design and implementation of time synchronization for CNC systems which employed switched Ethernet as its communication module. J. Liu et al. [9] designed an embedded open architecture CNC system based on industrial Ethernet using FPGA (Field Programmable Gate Array) technology, which was tested to be precise and effective on a three-axis milling machine. B. Li et al. [10] introduced an open architecture of CNC system based on EtherCAT network to provided higher transmission speed and greater data transfer bandwidth.

Owing to the development of image processing technology, it has become one trend to apply machine vision in the new generation of numerical control systems. Daniel Hanafi et al. [11] designed an active axis control system for conventional CNC machine which used visual feedback to track profile and improve the accuracy. Jurkovic et al. [12] proposed a reliable direct measuring procedure for measuring different tool wear parameters using a CCD vision system. Klancnik S. and Senveter J. [13] developed a numerical control system for optical determination of workpiece origin using QuickCam camera, which was tested to be reliable and adequate. Ghassan Al-Kindi and Hussien Zugaaher [14] provided a new CNC system integrated with vision-
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Based on feedback control. It was used for surface roughness measurement to improve the preciseness of manufactured parts.

Although many researches have been done in relevant fields, a referable standard for machine vision oriented CNC system has not performed. Very few studies have been done in integrating machine vision into grinding machine. Hence, it’s urgent to construct a machine vision oriented open architecture CNC system for profile grinding in order to innovate traditional optical enlargement based profile curve grinding method. The purpose of this study is to propose a novel artificial vision oriented numerical control method for precision profile curve grinding.

In this study, the design methodology for machine vision oriented profile grinding numerical control system was proposed. The principle of digital profile grinding was introduced in section 2. The structure of the hardware system and the software design methodologies were discussed in section 3. Finally, grinding experiments were conducted in section 4.

II. THE PRINCIPLE OF MACHINE VISION BASED PROFILE GRINDING

The testbed of machine vision based profile grinding is shown in Figure 1. Before operation, a workpiece fixed on the workbench so that the profile of the workpiece could be easily obtained by the CCD camera. Profile grinding is the study of point dry curve grinding. During operation, the grinding wheel rotated at high speed controlled by the motion controller and moved up and down circularly driven by the sliding table of the Z-axis. According to the camera field of view and the active condition of servo axes, two different kinds of machining modes were defined as local-visual-image-based profile grinding and global-visual-image-based profile grinding, which was used to match the size of the workpiece. During the process of local-visual-image-based profile grinding, the sliding tables of the X-axis and Y-axis were driven to provide feed motion. And only part of the profile was monitored by the CCD camera. While in the process of global-visual-image-based profile grinding, the sliding table of the U-axis and V-axis were driven to provide feed motion and the whole profile of the workpiece was obtained through the machine vision system.

![Figure 1: Structure of profile grinding machine.](image)

1 - machine bed; 2 - sliding table of U-axis; 3 - sliding table of V-axis; 4 - sliding table of Z-axis; 5 - motion controllers; 6 - position sensor; 7 - industrial/personal computer; 8 - CCD camera; 9 - telecentric lens; 10 - three-dimensional sliding table; 11 - camera supporter; 12 - grinding wheel; 13 - workpiece; 14 - workbench; 15 - light source; 16 - sliding table of Y-axis; 17 - sliding table of X-axis

A critical module of machine vision based profile grinding image collection and processing module was designed. Including the CCD camera, telecentric lens, parallel light source and IPC. During the process of grinding, each time when the grinding wheel reached the culminating point, the direction of the Z-axis was transmitted from the position sensor to the CCD camera through motion controller and IPC, and an image was taken and transmitted to IPC through the gigabit industrial Ethernet. The actual profile of the workpiece was extracted through image processing module integrated in IPC, and was compared with the theoretical profile for error detection and compensation.

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III. DESIGN METHODOLOGY FOR MACHINE VISION ORIENTED OPEN CNC SYSTEM

3.1 Hardware structure design of open profile grinding CNC

Figure 2 shows the modularized design of the hardware structure including HMI, motion control module, execution module, and image collecting module.

The HMI module includes an IPC and a front panel. The IPC provides the platform for software of the upper computer to run. The IPC is responsible for user administration, parameter determination, text file edit, processing condition monitoring, online profile extraction and error compensation. The operation panel was in charge of common functions of conventional CNC machine.

Figure 2: Hardware structure of open profile grinding CNC

The motion control module includes an embedded motion controller with bus interface. Here we call it a lower computer compared with the IPC which is called the upper computer. The embedded motion controller is controlled by the execution module through EtherCAT bus and communicated with the IPC through Ethernet TCP (Transmission Control Protocol). The application of EtherCAT bus simplified the connection and promoted the reliability and efficiency of data transmission.

The execution module included servo motors and their drivers, feedback encoders and actuators. The image collecting module was mainly made up of a digital CCD camera.

3.2 Software design of open CNC for profile grinding

3.2.1 The multi-thread architecture design

The structure of CNC system software is presented in Figure 3. Multi-thread architectures were applied in both upper computer and lower computer software architecture. The upper computer software includes G-code files, management thread, and image processing thread. The lower computer is consisted of three threads. Thread I is responsible for G-code interpretation and tool compensation, thread II processes error compensation through virtual axis technology and thread III executes the motion results from thread I. With the time sequences, design of threads, thread I and thread III alternately access the same memory space to ensure the efficiency and stability of the lower computer software. ActiveX control is used to provide data transmission between upper computer and lower computer.
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[Image: Figure 3: The structure of CNC system software.]

The upper computing software is mainly responsible for non-real-time tasks with complex algorithms, including function modules such as file management, parameter setting, communication control, condition monitoring, image processing, and error compensation. The file management is in charge of checking the grammar of the files, and providing toolpath simulation to avoid interference. Parameter setting is one of the basic parameters for the CNC system to run. Communication control answers for realizing real-time transmission of data through communication protocols between the upper computer and the lower computer. Condition monitoring is to obtain and display real-time motion parameters during the machining process, and provide protection when an abnormal condition occurs. Image processing is responsible for extracting the real profile of the workpiece from the image through filtering, thresholding, and edge extraction, and calculating the direction and magnitude of compensation.

The lower computer software was mainly responsible for real-time tasks such as parameter initialization, G-code interpretation, tool compensation, velocity look-ahead, and O/p control. Parameter initialization is to initialize the machine parameters before new processing to eliminate influence of redundant data generated in former machining. G-code interpretation is in charge of compiling the G-code files into object codes for the lower computer to execute directly. Tool compensation is used to compensate the radius of the tool based on C-function cutter radius compensation algorithm. Velocity look-ahead is responsible for providing velocity planning, turn point generation when the velocity changing rapidly, interference avoidance of the motor, inertia and guarantee the accuracy of the processing track. Error compensation is in charge of comparing the real profile with the theoretical one, calculate parameters for error compensation, and control the lower computer to execute compensation through virtual axis technology.

3.2.2 The characteristics of software design for profile grinding

The CNC system software was developed to meet the requirements of complex profile grinding with the following characteristics.

(1) Multi-thread architecture of the lower computer system

The algorithm that adopting microline blocksto make curve approximation has been commonly applied in grinding complex curve profile. However, the amount of code is incredibly huge after encoding and tool compensation. Limited by the computing power and data storage space of the embedded microcontroller, conventional single-thread architecture of the lower computer is considered to be time-consuming and ineffective. Hence, multi-thread architecture of the lower computer system was designed in this study to solve this problem.
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Figure 4: The process of multi-thread accessing memory space.

The process of multi-thread accessing memory space is presented in Figure 4. The memory space for storing results of encoding and tool compensation was divided into two parts, and two types of states were defined. For state 1, the thread put the result of encoding and tool compensation into result area 1 while thread III executed the result stored in result area 2. And for state 2, the thread put the encoding result into result area 2 while thread III executed the result stored in result area 1. During the machining, the two operating states were implemented alternately until the end of processing. This kind of architecture was proved secure and effective in the later experiment.

(2) Integrating of CNC HMI with image processing

HMI is an important part of the CNC system to provide a convenient operational environment for users. This paper presented a design of HMI integrating with image processing. Besides the basic functions such as parameter setting, text file management, program track simulation, the HMI also contains functions including image calibration, online visual monitoring, real-time profile error tracking and feedback.

During the machining process, a image was taken and transmitted to the upper computer, and the actual profile of the workpiece was extracted through image filtering, thresholding, and edge extraction. After comparing the actual profile with the theoretical one, parameters for error compensation were calculated and displayed. All the information was shown on the screen and accessible during the entire process.

(3) Virtual axis based on online error compensation

Figure 5: Virtual axis based compensation mechanism

The realization of reliable online error compensation has always been a challenge in conventional CNC system. In order to solve the problem of motion coupling during online error compensation, virtual axis technology has been implemented into CNC system. The mechanism of virtual axis compensation is presented in Fig. 5. The online compensation was realized by superimposing the motion of virtual axis on the motion of physical axis. The direction and amount of compensation motion was determined by image processing based algorithm in upper computer.

IV. EXPERIMENTS

4.1 Experimental setup

Grinding wheel profile dressing experiment was designed to testify the developed machine vision oriented CNC architecture and algorithms. The prototype CNC system was applied in the self-developed profile grinding testbed shown in Figure 6. The upper computer of the CNC was an i7-8700 with 16-GBytes RAM and 128-Gbyte hard drive. The lower computer was

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anembeddedmotioncontrollerTrioMC664-X withaquadcore1-GHZ ARM9CPU. The communicationoff the CNCsystemwasbasedonreal-time industrial Ethernet. A six-megapixel CCD camera GC2441M made in Germany was used in machine vision system.

An undressed grinding wheel was used to grind the diamond dresser following a given trajectory. The vitrified bond grinding wheel, produced by Saint-Gobain, is comprised of chrome corundum abrasive with 120 mesh size. The size of grinding wheel is 150 mm in diameter and 6 mm wide. The circular profile of arc wheel can be dressed by the diamond dresser. First, dress the double bevel of the grinding wheel. Then, dress the wheel arc. The theoretic radius of wheel arc R is 2.17 mm, the central angle of wheel arc α is 90° and the included angles β₁ and β₂ are 45°. The nose profile shape of the wheel before dressing is shown in Figure 7(a). The theoretical dressed profile is shown in Figure 7(b), and the actual profile after dress is image captured and shown in Figure 7(c).

![Figure 6: Self-developed profile grinding testbed.](image)

![Figure 7: The nose shape of the wheel (a) original profile; (b) theoretic profile; (c) actual profile.](image)

After grinding, the profile of the dressed wheel was extracted by the machine vision system and compared with the theoretic profile. The machine vision system was calibrated before the experiment. The accuracy of calibration board is 1 μm. The pixel size of this CCD camera was calibrated to be 3.48 μm.

4.2 Experimental results

The actual profile of the dressed wheel was obtained after image processing, and the radius of wheel arc was calculated using a least squares method. The results showed that the actual radius of wheel arc was 2.10 mm, and the radius error was less than 2% comparing with the theoretic radius of wheel arc. The roundness error was less than 0.022 mm.

Furthermore, the profile of the dressed wheel was measured by different methods to verify the reliability of profile visual measurement. Due to the profile of the grinding wheel was difficult to be measured directly, a copy of the grinding wheel profile was obtained by grinding graphite carbonboard using the dressed wheel. The copy of the grinding wheel profile could be measured by an optical profiler model KS1100 produced by Keyence. The profile parameters of the dressed wheel were calculated based on three methods including processing of in-situ grinding wheel image, processing of profile copy image on the graphite carbonboard, and optical profiler measuring the profile copy, which were...
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illustrated in Figure 8. The computing result of profile parameters were listed in Table 1. The relative error of the measurement results based on the method were less than 0.7%. The results not only proved the measurement accuracy of the machine vision system, also verified the feasibility of the architecture and algorithm of the designed CNC system.

In order to evaluate the performance of the error compensation algorithm, the computing method of actual machining errors is shown in Figure 9. Suppose a curve profile is from \( W_0 \) to \( W_n \). At an arbitrary point \( W_i \), define the error \( h_i \) of this point as the distance between theoretic track and actual track of the cutter center in the normal direction.

![Figure 8: Profile measurement based on different methods (a) grinding wheel image; (b) profile copy image; (c) profile measured by optical profiler.](image)

Table 1: Computation of grinding wheel profile parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Image of the grinding wheel</th>
<th>Image of the profile copy</th>
<th>Profile measured by optical profiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Included angle ( \beta_1 )</td>
<td>45.44</td>
<td>45.58</td>
<td>45.79</td>
</tr>
<tr>
<td>Included angle ( \beta_2 )</td>
<td>45.07</td>
<td>45.13</td>
<td>45.36</td>
</tr>
<tr>
<td>Radius of wheel arc ( R ) [mm]</td>
<td>2.128</td>
<td>2.132</td>
<td>2.139</td>
</tr>
<tr>
<td>Roundness [mm]</td>
<td>0.025</td>
<td>0.027</td>
<td>0.034</td>
</tr>
</tbody>
</table>

![Figure 9: Quantification of actual machining trajectory errors.](image)

The grinding wheel was dressed twice with and without error compensation. The parameters were calculated from the image of the grinding wheel captured by CCD camera and the results were listed in Table 2. The relative error between actual value and target value of each parameter decreased more.
than0.5percentageerrorcompensationalgorithmbeingimplemented. Thereresultverifiedthevalidityoftheerrorcompensationalgorithmbasedonvirtualaxis.

Table 2: Computation of parameters with and without error compensation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Without error compensation</th>
<th>With error compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Included angle $\beta_1$</td>
<td>Target value: 45</td>
<td>Actual value: 45.44</td>
</tr>
<tr>
<td></td>
<td>Relative error [%]</td>
<td>0.98</td>
</tr>
<tr>
<td>Included angle $\beta_2$</td>
<td>Target value: 45</td>
<td>Actual value: 45.07</td>
</tr>
<tr>
<td></td>
<td>Relative error [%]</td>
<td>0.16</td>
</tr>
<tr>
<td>Central angle of wheel arc $\alpha$</td>
<td>Target value: 90</td>
<td>Actual value: 90.61</td>
</tr>
<tr>
<td></td>
<td>Relative error [%]</td>
<td>0.68</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The integration of machine vision into motion control of machine tool has become an inevitable trend to construct the new generation of numerical control systems. In this paper, a machine vision oriented open numerical control system was studied for complex profile grinding. The hardware and software architectures of the system were established. The new characteristics of the control system include the multi-thread mechanism in both the upper and lower computers, the fusion of human-machine interaction and image processing, virtual axis-based machining error compensation. The critical issues for memory management of machine vision-based open CNC system were resolved by multi-thread architecture design and algorithm development. The proposed numerical control system was implemented in the developed platform. The experiments were designed to verify the feasibility of the developed technologies for machine vision-oriented open CNC profile grinding. The results indicated that the developed CNC system can meet the essential requirements of the new generation of profile grinding machine. Future work will focus on the optimization of image processing and error compensation algorithms to further improve the precision of the profile grinding.

VI. REFERENCES


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