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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; Numerial control; System; Imaging processing*

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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 Xiao-ming 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 Zughaer [14] provided a new CNC system integrated with vision-based 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 visionoriented 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

Thetestbedofmachinevisionbasedprofilegrinding isshowninFigure1.Before operation,a workpiecewasfixedontheworkbenchsothattheprofileoftheworkpiececouldbeeasily obtained bytheCCDcamera.Profilegrindinginthisstudyisapointdrycurvegrinding.Duringoperation,the grindingwheelrotatedathighspeedcontrolledby motioncontrollerandmovedupanddown circularly driven by theslidingtableofZ-axis.Accordingtothecamerafieldofviewandtheactive conditionofservoaxes,twodifferentkindsofmachining modeweredefinedaslocal-visual-image-basedprofilegrinding andglobal-visual-image-basedprofilegrinding,whichwasusedtomatchthe sizeoftheworkpiece.During theprocessoflocal-visual-image-basedprofilegrinding,thesliding tablesofX-axisandY-axisweredriventoprovidefeedmotion,andonly partoftheprofilewas monitoredby theCCDcamera.Whileinprocessingofglobal-visual-image-basedprofilegrinding, theslidingtablesofU-axisand V-axisweredriventoprovidefeedmotionandthewholeprofileof the workpiecewas obtained through the machine vision system.

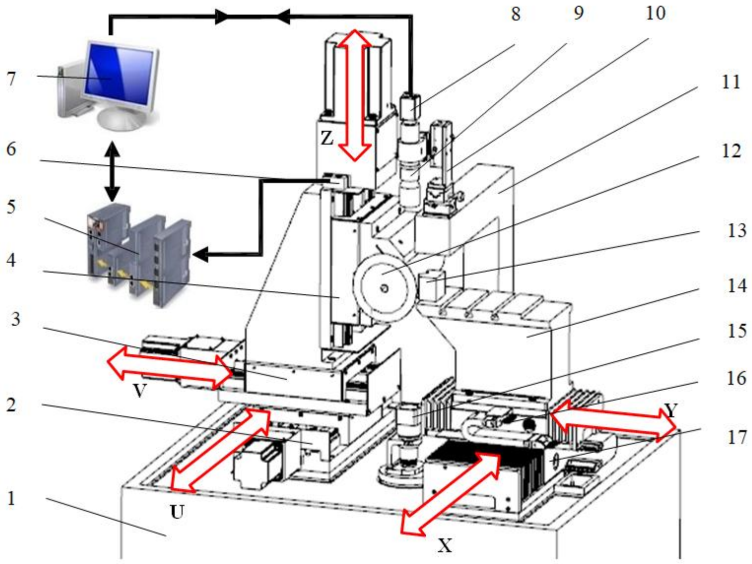

Figure 1:Structureof profilegrindingmachine.

1 - machine bed;2 - sliding table ofU-axis;3 - sliding table ofV-axis; 4 - sliding table ofZ-axis; 5 - motion controllers; 6 - position sensor; 7 - industrialpersonalcomputer; 8 - CCDcamera; 9 - telecentric lens; 10 - three-dimensionalsliding table; 11 - camera supporter; 12 - grinding wheel; 13 - workpiece; 14 - workbench;15 - lightsource;16 - slidingtable ofY-axis;17 - sliding table ofX-axis

Ascriticalmodule of machinevisionbasedprofile grinding,imagecollectingandprocessing modulewasdesignedincluding CCDcamera, telecentriclens, parallellightsourceandIPC.During theprocessofgrinding,eachtimewhenthegrindingwheelreachedtheculminatingpointindirection ofZ-axis,asignalwastransmittedfromthepositionsensortoCCDcamerathroughmotioncontroller andIPC,andanimagewastakenandtransmittedtoIPCthroughgigabitindustrialEthernet. The actualprofileoftheworkpiecewasextractedthroughimageprocessing moduleintegratedinIPC, and was compared withthetheoretical profileforerror detection andcompensation.

III. DESIGN METHODOLOGY FOR MACHINE VISION ORIENTED OPEN CNC SYSTEM

3.1 Hardware structure design of open profile grinding CNC

Figure2showsthemodularizationdesignofthehardware structureincluding HMI,motioncontrol module, execution module and imagecollectingmodule.

The HMI module includedanIPCandanoperationpanel.TheIPCprovidedtheplatformfor softwareofuppercomputer torun.TheIPCwasresponsibleforuseradministration,parameter determination,textfile edit,processingconditionmonitoring,onlineprofileextractionanderror compensation.The operationpanelwasincharge of commonfunctionsof conventionalCNC machine.

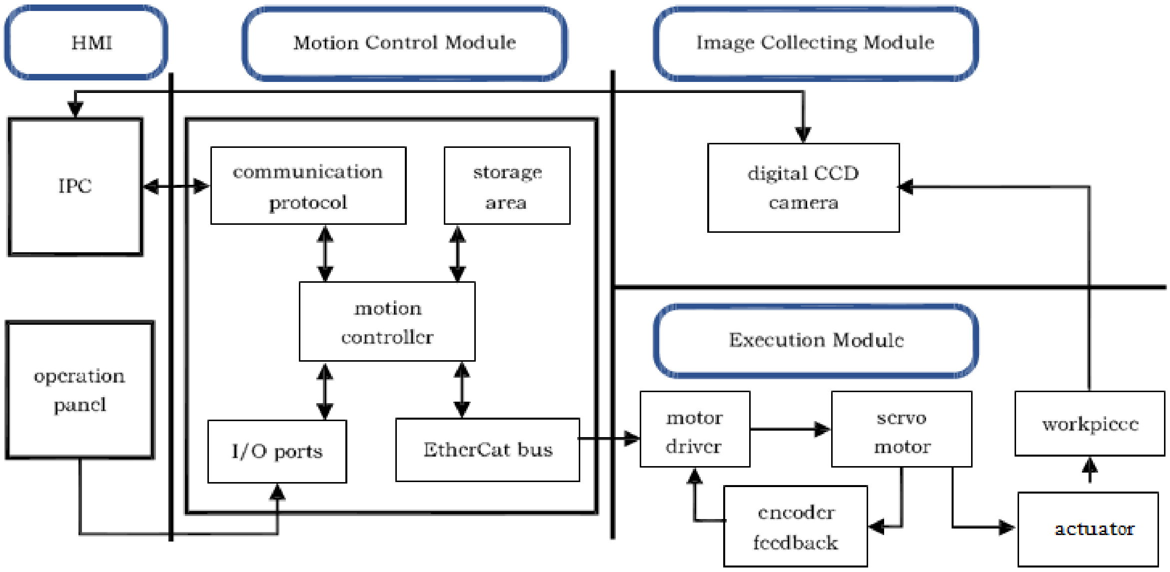

Figure 2:Hardwarestructureof openprofilegrindingCNC

Themotioncontrolmoduleincludedanembeddedmotioncontrollerwithbusinterface.Here we callitlowercomputercomparedwiththeIPCwhichiscalleduppercomputer.Theembeddedmotion controllercontrolledexecutionmodulethroughEtherCatbusandcommunicatedwiththeIPCthrough EthernetTCP (TransmissionControlProtocol).TheapplicationofEtherCatbussimplifiedthe connection and promotedthereliabilityandefficiencyof 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 structureofCNC systemsoftwareispresentedinFigure3.Multi-thread architectures were appliedinbothuppercomputerandlowercomputersoftwarestructure.Theuppercomputersoftware includesG-codefiles managementthreadandimageprocessing thread.Thelowercomputeris consistedofthreethreads.ThreadI isresponsibleforG-codeinterpretationandtoolcompensation, threadII processeserrorcompensationthroughvirtualaxistechnologyandthreadIIIexecutesthe motionresultsfromthreadI.Withthetimingsequencedesignofthreads,threadI andthreadIII alternatelyaccessesthesamememory spacetoensuretheefficiencyandstability ofthelower computersoftware. ActiveXcontrolisusedtoprovidedatatransmissionbetweenuppercomputer and lower computer.

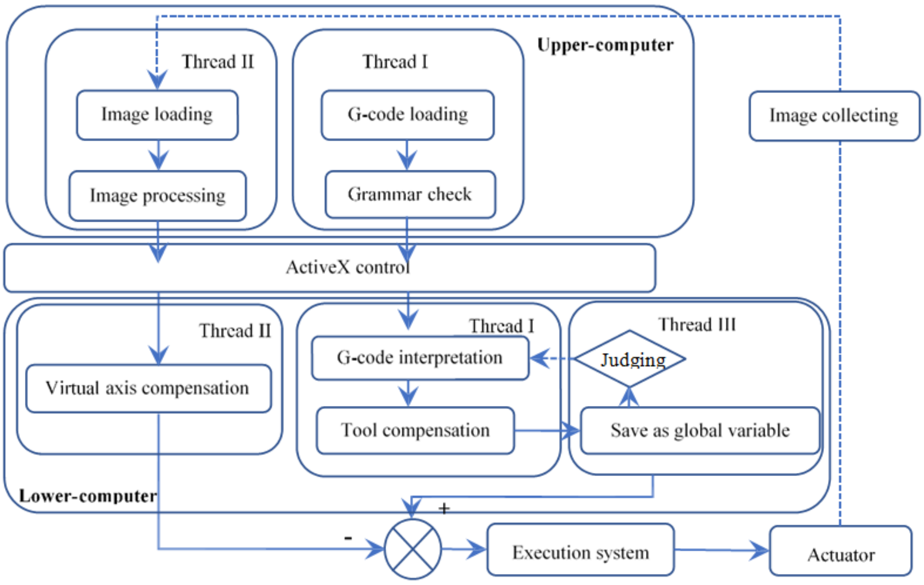

Figure 3:ThestructureofCNC systemsoftware.

Theupper computersoftware is mainlyresponsiblefornon-real-time tasks with complex algorithms,including functionmodulesastextfilemanagement,parametersetting,communication control,conditionmonitoring,imageprocessing anderrorcompensation.Textfilemanagementisin chargeofchecking thegrammaroftextfiles,andprovidetoolpathsimulationtoavoidinterference. Parametersetting istosetbasicparametersfortheCNC systemtorun.Communicationcontrol answersforrealizing real-timetransmissionofdatathroughcommunicationprotocolbetweenthe uppercomputerandthelowercomputer.Conditionmonitoring istoobtainanddisplay real-time motionparametersduring themachining process,andprovideprotectionwhenabnormalcondition occurs.Imageprocessingisresponsibleforextractingtherealprofileoftheworkpiecefromtheimage throughfiltering,thresholding andedgeextraction,andcalculating thedirectionandmagnitude of compensation.

Thelowercomputersoftwarewasmainly responsibleforreal-timetaskssuchasparameter initialization,G-codeinterpretation,toolcompensation,velocity look-aheadandI/Oportscontrol. Parameterinitializationistoinitializemachiningparametersbefore newprocessing toeliminate influence of redundantdatageneratedinformermachining.G-code interpretationisincharge of compile the G-code filesintoobjectcodesfor thelower computertoexecute directly.Tool compensation is used tocompensatethe radius ofthetool based on C-function cutterradius compensationalgorithm.Velocitylook-aheadisresponsibleforproviding velocityplanning atsharp turningpointsoftoolpathwhenvelocity changingrapidly,inordertoavoidinfluenceofthemotor inertiaand guaranteetheaccuracyofprocessingtrack.Errorcompensationisinchargeofcomparing the real profilewith thetheoretical one, calculateparameters forerror compensation, and control the lower computer toexecute compensation throughvirtual axis technology.

3.2.2 The characteristics of software design for profile grinding

TheCNC systemsoftware wasdevelopedtomeettherequirementsofcomplexprofilegrinding with the followingcharacteristics.

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

Thealgorithmthatadoptingmicrolineblocksto makecurve approximationhasbeencommonly appliedingrindingcomplexcurveprofile.However,theamountofcodeisincredibly hugeafter encodingandtoolcompensation.Limitedby thecomputingpoweranddatastoragespaceofthe embeddedmotioncontroller,conventionalsingle-thread architecture ofthelower computeris consideredto betime-consuming andineffective.Hence,multi-threadarchitecture ofthelower computer system was designed in this studyto solvethis problem.

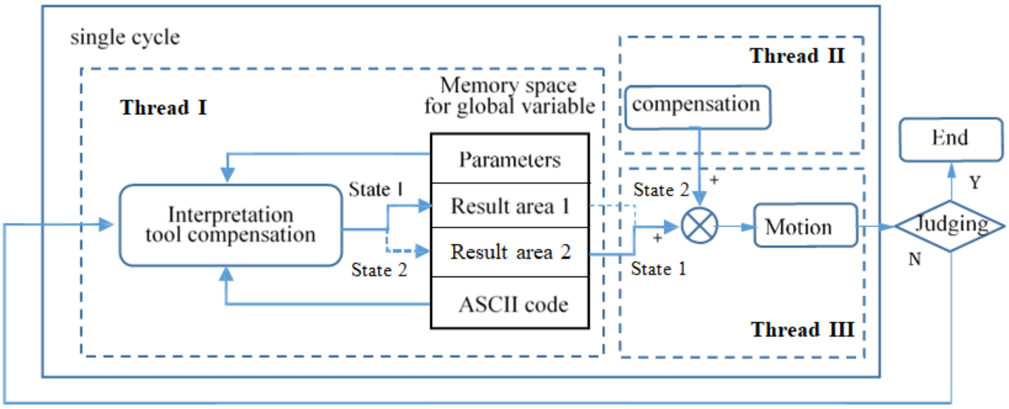

Figure 4: The process of multi-thread accessing memory space.

Theprocessofmulti-threadaccessingmemoryspaceispresentedinFigure4.Thememoryspacefor storingresultsofencodingandtoolcompensationwasdividedintotwoparts,andtwotypesofstates weredefined.Forstate1,threadIputtheresultsofencodingandtoolcompensationintoresultarea 1whilethreadIIIexecutedtheresultsstoredinresultarea2.Andforstate2,threadIputtheencoding resultsintoresultarea2whilethreadIII executedtheresultsstoredinresultarea1.Duringthe machining,thetwooperatingstateswereimplementedalternatelyuntiltheendofprocessing.This kind of architecturewasproved secure andeffective in thelater experiment.

(2) Integrating of CNC HMI with image processing

HMI isanimportantpartoftheCNCsystemtoprovideconvenientoperationalenvironmentfor users.ThispaperpresentedanewdesignofHMIintegratingwithimageprocessing.Besidesthebasic functionssuchasparametersetting,textfilesmanagement,processtracksimulation,theHMI also containedfunctionsincluding imagecalibration,onlinevisualmonitoring,real-timeprofileerror trackingand feedback.

Duringthemachiningprocess,animagewastakenandtransmittedtotheuppercomputer,andthe actualprofile ofworkpiece wasextractedthroughimage filtering,thresholdingandedge extraction. Aftercomparing theactualprofilewiththetheoreticalone,parametersforerrorcompensationwere calculatedanddisplayed. Allinformationwasshownonthescreenandaccessibleduringtheentire process.

(3) Virtual axis based online error compensation

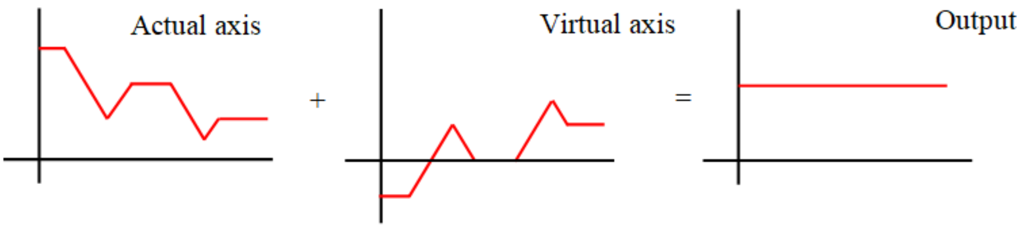

Figure 5:Virtual axisbasedcompensationmechanism

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

Grindingwheelprofiledressingexperimentwas designed totestifythedevelopedmachinevision orientedCNCarchitecture andalgorithms.TheprototypeCNCsystemwasappliedintheself-developedprofilegrindingtestbedshowninFigure6.Theupper-computeroftheCNCwasanIPCwith aquadcore3.2-GHZ x64 CPU, 8-GbytesRAM and128-Gbyteharddrive. Thelowercomputer was anembeddedmotioncontrollerTrioMC664-Xwithaquadcore1-GHZ ARM9CPU.The communicationoftheCNCsystemwasbasedonreal-timeindustrialEthernet.AfivemegapixelCCD cameraGC2441M madein Germanywas used inmachine 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 6mm 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 2.17mm, the central angle of wheel arc α is 90° and the included angles β_1 and β_2 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).

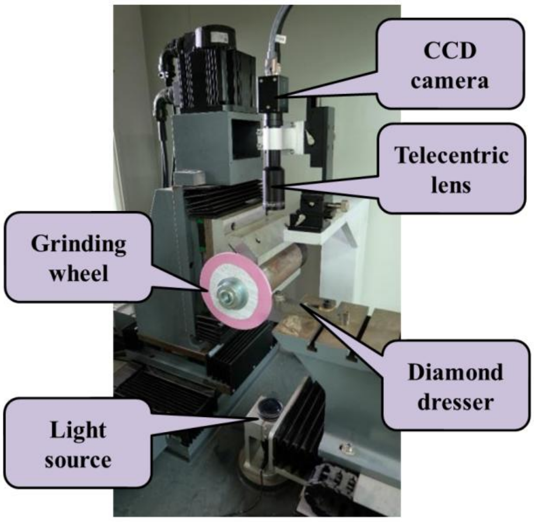

Figure 6: Self-developed profilegrindingtestbed.

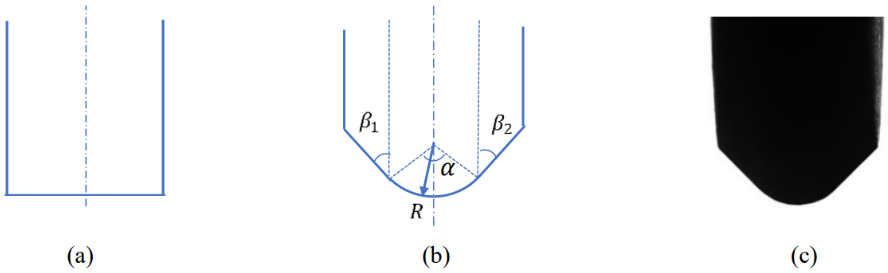

Figure 7:Thenoseshapeofthe wheel (a) original profile; (b)theoreticprofile;(c) actual profile.

Aftergrinding,theprofileofthedressedwheelwasextractedby themachinevision systemand comparedwiththetheoreticprofile.Themachinevisionsystemwascalibratedbeforetheexperiment. Theaccuracyofcalibrationboardis±1 μm.ThepixelsizeofthisCCDcamerawascalibratedtobe3.48μm.

4.2 Experimental results

The actualprofile of thedressed wheelwasobtained after image processing,andthe radiusof wheelarcwascalculatedusingleastsquaremethod.Theresultsshowedthattheactualradiusofwheel arcwas2.210 mm,andtheradiuserrorwaslessthan2%comparingwiththetheoreticradiusofwheel arc.Theroundnesserrorwas less than 0.022mm.

Furthermore,theprofileofthedressedwheelwasmeasuredbydifferentmethodstoverify the reliabilityofprofilevisualmeasurement.Duetotheprofileofthegrindingwheelwasdifficulttobe measureddirectly,acopy ofgrinding wheelprofilewasobtainedby grindinggraphitecarbonboard usingthedressedwheel.Thecopy ofgrindingwheelprofilecouldbemeasured byopticalprofiler modelKS1100producedby Keyence.Theprofileparametersofthedressedwheelwerecalculated basedonthreemethodsincluding processing ofin-situgrinding wheelimage,processingofprofile copyimageonthegraphitecarbonboard,andopticalprofilermeasuringtheprofilecopy,whichwere illustratedinFigure8. Thecomputing resultsofprofileparameterswerelistedinTable1. Therelative errorsofthemeasurementresultsbasedonthreemethodswerelessthan0.7%. Theresultsnotonly provedthemeasurementaccuracy ofmachinevisionsystem,alsoverifiedthefeasibility ofthe architectureandalgorithm of thedesigned CNC system.

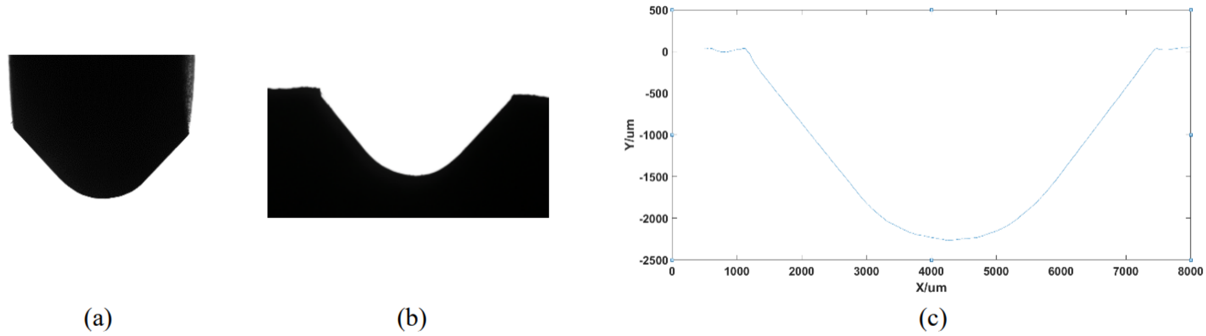

Figure 8: Profilemeasurement based on different methods (a)grindingwheel image; (b)profile copy image; (c) profilemeasured byoptical profiler.

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.

Table 1: Computationof grindingwheel profileparameters

Parameters	**Image of the grinding wheel**	**Image of the profile copy**	**Profile measured by optical profiler**
Included angleβ_1	45.44	45.58	45.79
Included angle β_2	45.07	45.13	45.36
Radius of wheel arc R [mm]	2.128	2.132	2.139
Roundness [mm]	0.025	0.027	0.034

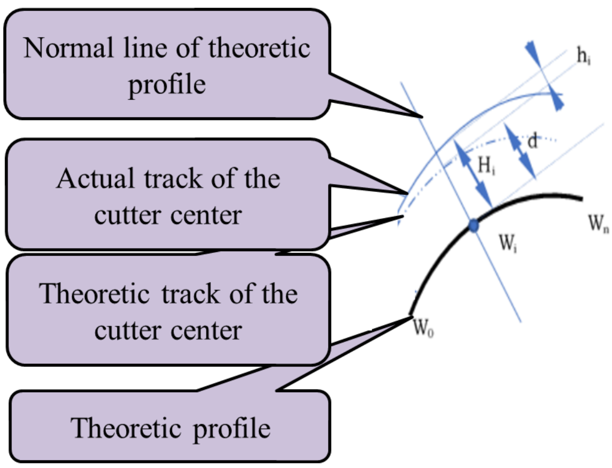

Figure 9: Quantification of actual machining trajectory errors.

Thegrindingwheelwasdressedtwicewith andwithouterrorcompensation.Theparameterswere calculatedfromtheimageofthegrindingwheelcapturedbyCCD camera andthe resultswerelisted inTable2.Therelativeerrorbetweenactualvalueandtargetvalueofeachparameterdecreasedmore than0.5percentaftertheerrorcompensationalgorithmbeing implemented.Theresultverifiedthe validityof theerrorcompensationalgorithmbased on virtual axis.

Table 2:Computationofparameters with and without error compensation

Parameters		Without error compensation	With error compensation
Included angle β_1	Targetvalue	45	45
	Actual value	45.44	45.01
	Relativeerror[%]	0.98	0.02
Included angle β_2	Targetvalue	45	45
	Actual value	45.07	44.89
	Relativeerror[%]	0.16	0.24
Central angle of wheel arc α	Targetvalue	90	90
	Actual value	90.61	89.90
	Relativeerror[%]	0.68	0.11

V. CONCLUSION

Theintegrationofmachinevisionintomotioncontrolofmachinetoolshasbecomeanewtrendto constructthe newgeneration ofnumericalcontrolsystems.In thispaper, amachine vision oriented opennumericalcontrolsystemwasstudiedforcomplex profilegrinding.Thehardwareandsoftware architecturesofthesystemwereestablished. Thenewcharacteristicsofthecontrolsysteminclude themulti-threadmechanisminbothupperand lowercomputers,thefusionofhuman-machine interactionandimageprocessing,virtualaxisbasedmachiningerrorcompensation.Thecriticalissues formemory managementofmachinevisionbasedopenCNC systemweresolved by multi-thread architecture designandalgorithmdevelopment.The proposednumericalcontrolsystemwas implementedintheself-developedprofilegrinding platform.Theexperimentsweredesignedto verifythefeasibilityofthedevelopedtechnologiesformachinevisionorientedopenCNCinprofile grinding. The resultsindicatedthatthe developedCNCsystemcanmeettheessentialrequirements ofnewgeneration ofprofilegrinding machine.Futureworkwillfocusontheoptimizationofimage processinganderrorcompensationalgorithmstofurtherimprovetheprecisionoftheprofilegrinding.

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