Control System Development of Large and High-groove Density Grating Ruling Engine Based on Real-time Virtual Hardware-in-the-loop Simulation

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***Abstract*—In this paper, the control system development of a large and high-groove density grating ruling engine is presented. The grating ruling engine considered here was designed to rule gratings with a maximum ruled area of 400 mm (groove length) × 500 mm (width) and a highest groove density of 6000 grooves/mm. Three kinds of blank motion (stop-and-go blank motion, continuous blank motion and hybrid blank motion) should be obtained. However the ultra-precision mechanical structure and complicated driving method result in a long development period. To shorten the development time, a pure software real-time simulator based on real-time virtual hardware-in-the-loop simulation was invented, which can implement concurrent development of hardware and software. In this simulator, all the hardware is virtual. Their appearance and operation are programmed to imitate corresponding physical prototypes. Control logic can be developed using the simulator. After simulation development completed, the simulator was used as the final control software directly and the control logic was ported to control the real-world grating ruling engine by rewriting a small portion of the source code. The real-world system level testing result proves that real-time virtual hardware-in-the-loop simulation is an effective and efficient approach for developing the control system of a complicated system.**

Keywords-control system development; control system simulation; virtual hardware; hardware-in-the-loop simulation; grating ruling engine.

I. INTRODUCTION

Grating manufacturing technology is one of the most sophisticated technologies nowadays. The diffraction grating ruling engine is known as the king of fine mechanics [1]. Up to now, the diffraction grating ruling engine produced by Hitachi of Japan possesses the highest precision, which has a ruling density of 10,000 grooves/mm with a maximum ruled area of 200 mm (groove length) × 300 mm (width) [2]. The objective of producing a grating ruling engine with groove density of 6000 grooves/mm and maximum ruled area of 400 mm (groove length) × 500 mm (width) should be achieved in our research. It is an ultra-precision mechanical structure by itself. In addition, three kinds of blank motion (stop-and-go blank motion, continuous blank motion and hybrid blank motion) to be realized, together with ultra-precision positioning requirement (periodic error is less than 5 nm), make the control system more complicated. As a result, both the manufacturing of the mechanical structure and the development of the control system need a long period. The simultaneous development of hardware and software is imperative, which will not only shorten the development period, but also reduce the development costs of hardware [3], [4].

To implement concurrent development, various simulation methods have been proposed, such as hardware-in-the-loop (HIL) simulation [5], [6], the virtual instruments software [4], [7] and MATLAB/Simulink software [8], [9]. Combining the advantages of HIL simulation and LabVIEW, an efficient development method called real-time virtual hardware-in-the-loop simulation is proposed in our research. Firstly, specific and independent software is developed. In this software, all of the hardware is virtual just like the instruments in LabVIEW. The appearance and operation of these virtual hardware are programmed to imitate their corresponding physical prototypes. Then the control logic is developed in this software. After simulation development completed, the simulation software is used as the final control software directly and the control logic is ported to control the real-world grating ruling engine by rewriting little source code.

In the following sections, a general description of the large and high-groove density grating ruling engine is given at first. The detailed control system development process using virtual HIL simulation is explained in Section Ⅲ. In this section, how to create a virtual HIL simulator, and how to develop the control system of a ruling engine in this simulator are both described. It can be seen that by using the virtual HIL simulation, control system can be developed quickly and easily. Both the system porting process and the real-world system level testing are presented in Section Ⅳ. The testing result proves the feasibility of putting virtual HIL simulation into control system simulation development. Conclusion followed in Section Ⅴ.

II. THE GRATING RULING ENGING

The 3D model of the grating ruling engine is shown in Fig. 1. It is a classical Rowland engine [10]. The relative motion between grating blank and ruling tool is explained in Fig. 2. The ruling tool makes reciprocating motion in the direction of ruling, and the blank carriage makes one-way movement perpendicular to the direction of ruling. Through the synthesis of the two movements, grating ruling motion is achieved.

The grating ruling engine is composed of indexing subsystem and ruling subsystem. The indexing subsystem drives the grating blank to do the indexing motion and the ruling subsystem drives the tool to make reciprocating motion along the tool bridge.

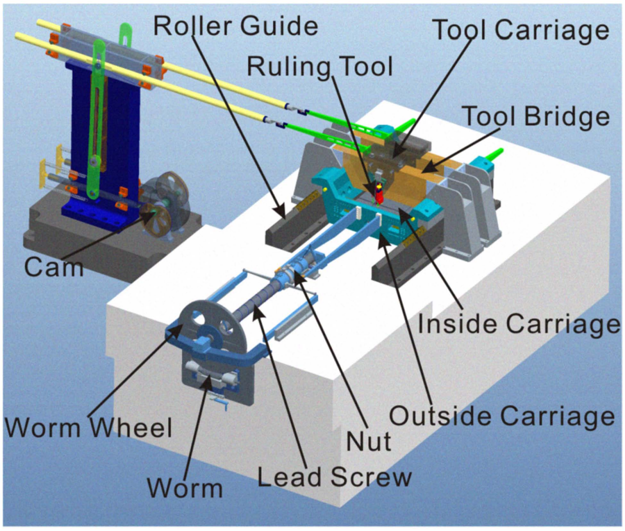

Figure 1. The 3D model of the diffraction grating ruling engine.

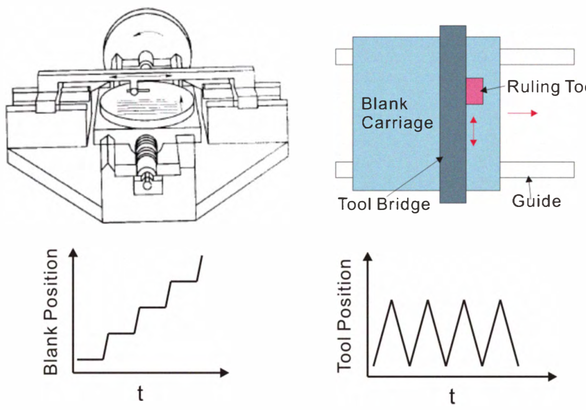

Figure 2. Movement pattern and motion traces of Rowland engine.

A. The Indexing Subsystem

The indexing subsystem consists of a worm gear pair, a lead screw-nut pair and a rolling guide pair. The inside carriage was hung on the outside carriage with four leaf springs. A grating blank was mounted on the inside carriage. The inside carriage can move without friction in the direction of groove spacing. Two piezoelectric (PZT) devices were symmetrically mounted between the inside and outside carriages. The length of these two devices can be varied so as to drive the inside carriage to move in the direction of groove spacing relative to the outside carriage. Position of inside carriage was detected by two dual-frequency laser interferometers. The driving chain of the indexing subsystem is shown in Fig. 3.

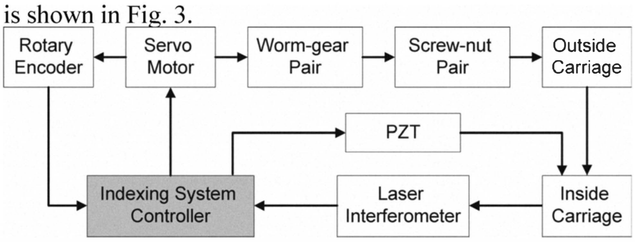

Figure 3. The driving chain of the indexing subsystem.

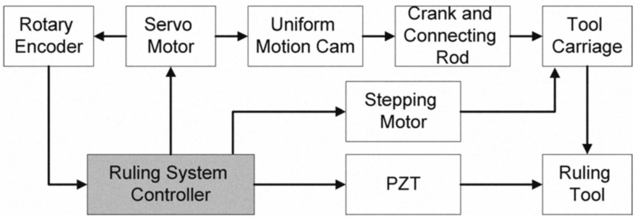

Figure 4. The driving chain of the ruling subsystem.

B. The Ruling Subsystem

The ruling subsystem includes two same ruling structures driven by only one servo motor. One ruling structure plays a role of balance. It is used to damp the vibration induced by reversing moving direction of the tool carriage. Another one drives the tool carriage to move in the direction of groove along the tool bridge. Then the ruling tool can be driven to move in the direction of groove. This subsystem includes a servo motor (driving the cam), a stepping motor (controlling the tool's direction) and a PZT device (driving tool up and down). The driving chain of the ruling subsystem is shown in Fig. 4.

III. The Control System Development

A method called real-time virtual hardware-in-the-loop simulation is adopted to implement concurrent development of the grating ruling engine. The control system can be developed before the physical engineering prototype is manufactured. Software implementing real-time virtual HIL simulation should be developed at first.

A. Construct the Simulation Software

In order to facilitate future code porting, the source code of the simulation software is divided into four layers: the graphic user interface (GUI) layer, the control logic layer, the hardware driver layer and the virtual hardware layer. And the source code of those layers running in different platforms should be relatively independent of each other. The architecture of the simulation software is shown in Fig. 5. The control logic layer and the hardware driver layer should be programmed in C language, since these two layers were designed to run in a DSP (Digital Signal Processor). Because the source code of the virtual hardware layer need not be ported, it can be implemented in C++ which is easier to use than C. But its driving interface must be developed compatible with the hardware driver layer.

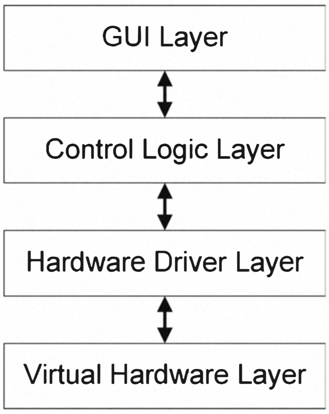

Figure 5. The architecture of the simulation software.

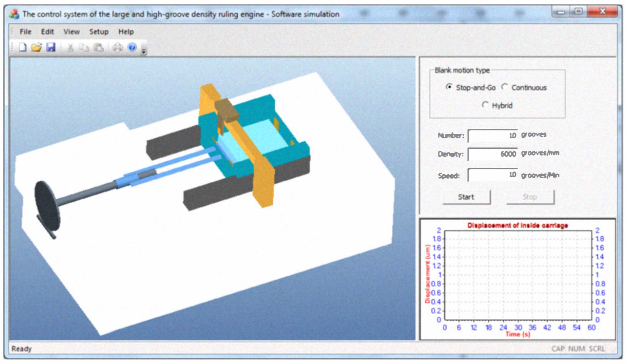

Figure 6. The GUI of the simulation software.

As the simulation software will be transplanted to the final control software of grating ruling engine, the GUI of the simulation software should be similar to the final control software. The GUI of the demo simulation software is shown in Fig. 6. It is a SDI (Single Document Interface) application built with Visual Studio 2008 IDE. The main view of the software is composed of three split windows: the virtual grating ruling engine window, the control panel window and the motion trace window. The virtual grating ruling engine window was implemented based on the OpenGL library. A virtual grating ruling engine which looked like the real one shown in Fig. 1 was displayed in this window. The movable mechanical parts of the virtual grating ruling engine can move along the specified traces. This window is an image feedback when debugging or testing the software and the control logic. Running information was also displayed. It helps the developers to determine whether the control logic algorithm is correct or not. Users control the grating ruling engine through the control panel window. The motion trace window shows the motion trace selected by the users. When the grating engine is running, the motion trace is updated in real-time. Then the running state of the ruling engine can be observed by the users.

TABLE I. THE MECHANISM REQUIRED TO BE INVENTED.

Mechanism	Function Requirements
The nut	Can move in the direction of groove spacing and driven by the servo motor of the indexing subsystem.
The outside carriage	Can move in the direction of groove spacing and driven by the nut.
The inside carriage	Can move in the direction of groove spacing and driven by the outside carriage.
The tool carriage	Can move in the direction of ruling and driven by the servo motor of the ruling subsystem and the stepping motor.
The tool	Can move up and down and driven by the tool carriage and a PZT device.

TABLE II. THE ACTUATORS AND SENSORS REQUIRED TO BE INVENTED.

Hardware	Function Requirements
Servo Motor	Driving the worm or the cam and having a encoder feedback.
PZT device	Driving the inside carriage or the tool.
Dual-frequency laser interferometers	Can feedback the position of inside carriage.
Stepping motor	Controlling the direction of the tool.

B. *Virtual Hardware Implementation*

According to the description of the grating ruling engine in Section Ⅱ, the mechanisms shown in table Ⅰ should be simulated. These mechanisms have been already established when developing the virtual grating ruling engine window of the simulation software presented in Fig. 6.

The actuators and the sensors required to be invented are shown in table Ⅱ. By using the object-oriented feature of C++, only one class is needed for one kind of hardware. For example, the three PZT devices can be defined with the same class CPZT which is programmed corresponding to the PZT device. The driving interfaces of virtual hardware provided to the hardware driver layer should be packaged to C function, since the hardware driver layer was written in C. In addition, all the interfaces of a virtual hardware class must be the same as the real-world hardware. For instance, the methods shown in table Ⅲ should be implemented in the class CPZT.

TABLE III. METHODS OF A VIRTUAL PZT DEVICE CLASS.

Methods	Description
bool SetLen(double len)	Set the length of the PZT device.
double GetLen(void)	Get the current length of the PZT device.

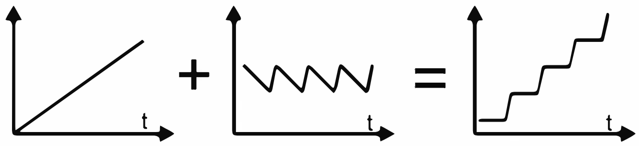

Figure 7. Motion traces of the two carriages and the PZT devices in hybrid blank motion mode.

C. Control Logic Development

Taking use of the functions of the hardware layer, control logic layer can be developed in the simulation software as traditional development process.

Three kinds of blank motion need be implemented in our research. They are stop-and-go blank motion, continuous blank motion and hybrid blank motion.

In classical and purely mechanical ruling engines, such as the Rowland engine, stop-and-go blank motion was customary [10]. The servo motor of indexing subsystem drives the inside carriage to move toward the approximate blank position until it is in the permitted range. Then the two PZT devices which are symmetrically mounted between the inside and outside carriages drive the inside carriage to move to the precise position. After that, the ruling subsystem lowers the tool by expanding the PZT device. Together with the reciprocating motion of ruling tool, grating ruling motion is achieved.

Continuous blank motion is usually adopted in modern ruling engines. Both of the servo motors of indexing subsystem and the ruling subsystem run at a constant speed all the time. So the inside carriage takes the grating blank to make uniform motion. And the indexing cycle and the tool movement cycle are same. When the blank moves to the groove position to be ruled, the tool should be just at the predetermined position, so that the ruling subsystem lowers the tool to start ruling.

Hybrid blank motion used in a ruling engine built by Hitachi of Japan is a mixed blank motion of stop-and-go and continuous. The servo motor of indexing subsystem runs at a constant speed all the time. So the outside carriage is moving in a constant speed continuously. The two PZT devices which are symmetrically mounted between the inside and outside carriages shrink so as to cancel the continuous translation of the outside carriage and to hold the inside carriage in the predetermined position. Stop-and-go motion is provided to the inside carriage by repeatedly expanding and shrinking the PZT devices, although a continuous translation is provided to the outside carriage by the screw mechanism. The motion traces of the inside carriage, the outside carriage and the PZT devices are shown in Fig. 7.

By using the simulation software, the control logic of above three kinds of blank motion was developed. Fig. 8 shows the simulated running state of stop-and-go blank motion mode. From the figure, we can see that stop-and-go motion of the inside carriage is achieved.

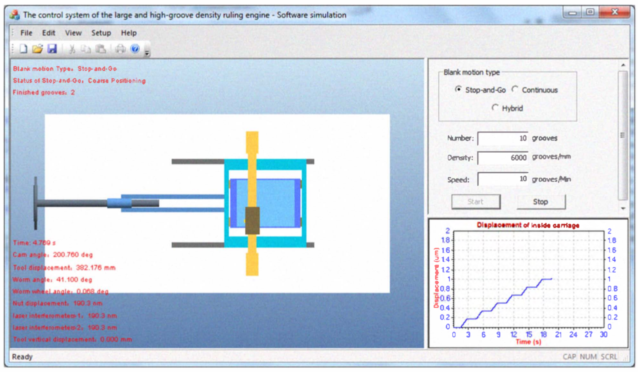

Figure 8. The simulation running state of stop-and-go blank motion mode.

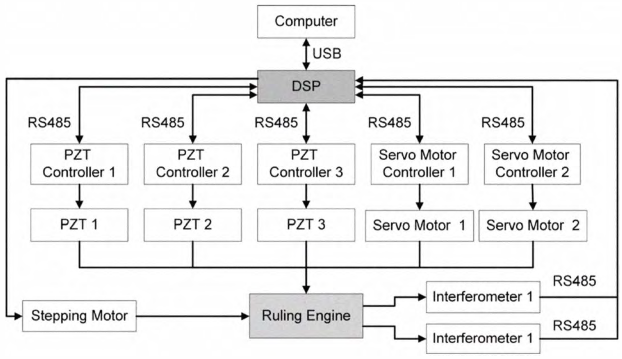

Figure 9. The block diagram of the control system.

IV. System Porting And Testing

The block diagram of the control system is shown in Fig. 9. The control software of the grating ruling engine was running in a PC. To gain higher stability, the source code of the control logic layer and the hardware driver layer were running in a DSP. The DSP is controlled by the control software through universal serial bus (USB). The PZT devices, the laser interferometers and the servo motors are all controlled by the DSP through their own controller. The DSP communicates with these controllers by RS485. The stepping motor in charge of the direction of the diamond tool is controlled by DSP directly.

After the simulation development is completed, the simulation software needs to be ported to adapt to the real-world target system. The source code of the GUI layer can be used directly. Since the architectural difference exist between PC platform and DSP, a small portion of the source code of the control logic layer have to be adapted. The virtual hardware is replaced by real-world hardware. And the functions of the hardware driver layer were re-implemented base on the real-world hardware. For example, the functions of the hardware driver layer which were used to control virtual PZT device can be re-implemented by sending commands to the controller of the real-world PZT device.

The system level testing is required after the porting work is done. The bugs generated when replacing virtual hardware with real-world hardware will be found during system level testing. The deficiency of the control logic developed in simulation stage can also be found.

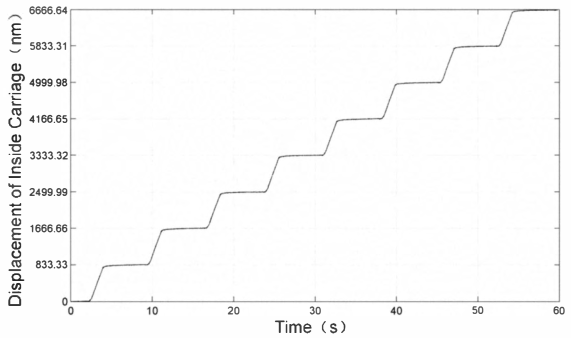

Figure 10. The motion trace of the inside carriage in stop-and-go blank motion mode.

Fig. 10 shows the testing result of the inside carriage displacement. It is tested in the stop-and-go blank motion mode and groove density is 1200 grooves/mm. It is consistent with the simulated result in Fig. 8. This testing result proves that control system can be developed quickly and inexpensively by using real-time virtual HIL simulation.

V. CONCLUSION

The control system development process of a large and high-groove density grating ruling engine is described in this paper. A method called virtual hardware-in-the-loop simulation has been used in the development. This method implements real-time simulation in a pure software environment with virtual hardware-in-the-loop simulation. At first, specific and independent simulation software was developed. In this software, all hardware of the grating ruling engine was simulated with virtual hardware. Then, the control logic was developed before the engineering prototype was manufactured. In this way, the control system can be developed simultaneously with ruling engine manufacturing. After simulation development was completed, the control system was ported to the real-world grating ruling engine. The system level testing results indicates that the control system of the grating ruling engine can be developed by the proposed approach correctly and inexpensively, and the development period is significantly reduced. It also confirms the feasibility of the approach in control system development.

REFERENCES

[1] Shi Lun, Hao Defu and Qi Xiangdong, "High precision photoelectric diffraction grating ruling engine," Chinese Journal of Scientific Instrument, vol. 22, no. 4, 2001, pp. 103-104.

[2] Toshiaki Kita and Tatsuo Harada, "Ruling engine using a piezoelectric device for large and high-groove density gratings," Appl. Opt, 1992, 31:1399.

[3] Kako Junichi, Naozumi Okuda and Akira Ohata, "Efficient control system development using model based development," in 27th Chinese Control Conference, CCC, July 16, 2008 - July 18, 2008, Kunming, Yunnan, China, 2008, pp. 582-585.

[4] Xiang Xuejun, Xia Ping, Yang Sheng and Liu Ping, "Real-time digital simulation of control system with LabVIEW simulation interface toolkit," in 26th Chinese Control Conference, CCC 2007, July 26, 2007 - July 31, 2007, Zhangjiajie, China, 2007, pp. 318-322.

[5] Kim Hajin J. and Moss Stephen G. "Common hardware-in-the-loop development," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing XIV, April 13, 2009 - April 13, 2009, United states, 2009, p. The International Society for Optical Engineering (SPIE).

[6] Cai Guowei, Chen Ben M., Lee Tong H. and Dong Miaobo, "Design and implementation of a hardware-in-the-loop simulation system for small-scale UAV helicopters" Mechatronics, vol.19, pp. 1057-1066, 2009.

[7] Wei Chao-Huang and Wu Chih-Hsing, "A simulator of winding machine controller using lab view environment," in 8th International Conference on Control, Automation, Robotics and Vision (ICARCV), December 6, 2004 - December 9, 2004, Kunming, China, 2004, pp. 2105-2110.

[8] Wahyunggoro Oyas and Saad Nordin B., "Development of fuzzy-logic-based self tuning PI controller for servomotor," in 2008 10th International Conference on Control, Automation, Robotics and Vision, ICARCV 2008, December 17, 2008 - December 20, 2008, Hanoi, Viet nam, 2008, pp. 1545-1550.

[9] Jia J., Lian D. and Wang Y., "Matlab / simulink based-study on PEM fuel cell and battery hybrid system," in 2008 10th International Conference on Control, Automation, Robotics and Vision, ICARCV 2008, December 17, 2008 - December 20, 2008, Hanoi, Viet nam, 2008, pp. 2108-2113.

[10] G. W. Stroke, "Diffraction gratings," in Optische Instrumente, Band 29 of Handbuch der Physik, S. FlUgge, ed. (Springer-Verlag, Berlin, 1967).