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Digital Implementation of A Galvanometric Optical Scanner Based on DSP and FPGA

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***Abstract*—A galvanometric optical scanner in a laser marking system is controlled to achieve the demand of high speed and high accuracy. This paper presents a design of digital galvanometric optical scanner adopting a high-precision PID control algorithm with compensation based on repetitive control which is DSP+FPGA-based architecture. This thesis consists of three parts including theory of laser marking system and galvanometer scanner construction, hardware design of DSP+FPGA-based architecture, design and Simulation of scanning controller.**

Keywords-galvanometer; high speed; high accuracy; repeatability; DSP; FPGA;USB；PID; compensation

I. INTRODUCTION

In processing industry, laser marking system is mainly used in the precision-machining, which requires high accuracy. A galvanometer scanner is the core of galvanometer laser marking system. The speed and accuracy of the galvanometer scanner determine the final effect of marking. In current, analog galvanometer scanner in laser marking system is still dominant. However, as the increasing accuracy demand of product processing, digital galvanometer scanners, with smaller size, higher precision and speed, etc, than former, will gradually replace analog galvanometer scanner, and have a good prospect of application in laser processing industry.

With the rapid development of electronics and the requirement of customers, digital signal processor DSP with powerful ability of signal processing, and field programmable gate array FPGA with an abundant of extended interface and logic circuits design, make a likelihood of galvanometer scanning system with high speed. The development of sensor in galvanometer, from photoelectric sensor to grating sensor, makes it possible to achieve highly accurate position measurement.

II. THEORY

Figure 1 shows the working principle of galvanometer-type laser marking system. The system consists of laser, optical system, computer, galvanometer scanner system, cooling systems, power supply and controller. Beam of laser, through optical system, is reflected by the X-axis and two Y-axis mirror of galvanometer scanner to the table of the XY projection plane to form a scan point. So any complex image can be marked by controlling the two specula of galvanometer scanners.

The laser for marking contains carbon dioxide laser, semiconductor laser and fiber laser, in which carbon dioxide laser has the maximum power and fiber laser has the smallest power. The different processing objects and precision determine the choice of laser source. The main device in optical system is beam expander, function of which is to expand the laser beam. Larger beam size, focused by the field lens can get smaller size and better effect. Cooling system ensures that the marking system work properly. Carbon dioxide laser must be water-cooled because its power is large. It is enough for semiconductor laser and fiber laser using air-cooled. Power supply provides motility for the entire system, including laser power supply, cooling power supply, worktable power supply and galvanometer control system power supply, etc. The role of field lens is to focus the laser beam to get a smaller spot for the precise processing of product.

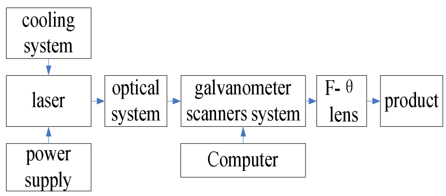

Figure 1. Working principle of galvanometer-type laser marking system.

According working principle of galvanometer laser marking system, you can see galvanometer scanning system is the heart of the whole system. The ultimate target of the marking system depends on the design of galvanometer scanning control system, so it is the focus of this article.

Galvanometer scanning system contains three parts: signal processing, feedback loops and the driver modules. Clearly signal processing system is the main design of the system. Microprocessor receives the image coordinates from host computer and the information of position from the sensor at the moment and calculates the value speedily using a certain algorithm. The processed data drives the galvanometer to marking location through driving circuit.

The schematic diagram shown in Figure 2:

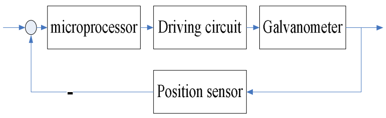

Figure 2. The schematic diagram of galvanometer scanning system.

Microprocessor, such as microcontroller, ARM, DSP, etc., mainly calculate the current controlling value through the control algorithm. So it should have the capabilities of high-speed data processing. Drive circuit mainly achieve signal conditioning like D/A converting, isolating, amplifying and others, and get the accurate value of mirror vibration control. Position sensor is used for measuring the current angle of galvanometer. Sensor should have high-precision position measurement capability used in system.

Galvanometer is an optical scanner with high accuracy, high speed and repeatability, including scanning mirror, position sensor, scanning motor and driving circuit, as shown in Figure 3. Its main properties include angle range, small-signal response time, repeatability, linearity and temperature drift. In actual project, two of the most important properties are the accuracy and speed.

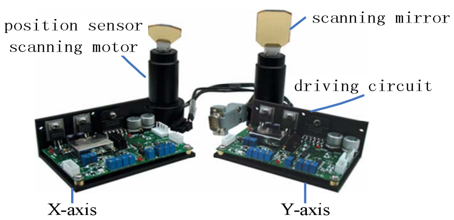

Figure 3. Composition principle of galvanometer.

Mirror aperture mainly depends on the effective diameter of the scanning beam, which is determined by the indicators of laser marking system. The higher precision, the greater effective diameter the system needs. The material of mirror depends on the laser wavelength. Different laser wavelengths are corresponding to different marking objects. For example, 10.64μm wavelength applies to most non-metallic materials, and 1064nm wavelength applies to metal materials.

According to the different angle sensor, the galvanometer can be divided into raster galvanometer and photoelectric galvanometer. Resolution of raster galvanometer is 0.46μrad, and the repeatability is 0.92μrad. Resolution of photoelectric galvanometer is 6μrad, and the repeatability is 12μrad. The application of raster in galvanometer achieves a high precision measurement, which provides a hardware foundation for the design of high precision galvanometer scanning system.

III. DSP+FPGA-BASED ARCHITECTURE

This system chooses DSP and FPGA as the core of signal processing.

PC is the information processing platform in this system, which sets and sends control instructions like completing the coordinate transformation, planning trajectory, rough interpolation computing, etc. The DSP is selected as the core of this system, which has tasks like completing data processing, running control algorithm and protecting interrupt handling. FPGA, as the co-processor chip, achieves grating signal acquisition, phase processing, internal conversion of data processed by DSP. The pre-and post-processing operations can focus on the complex algorithm implementation, and accelerate processing speed.

DSP is selected as the core of data processing, because DSP has two main advantages: firstly, the higher speed of computing, more precise numerical operations and faster responsiveness than microcontrollers; its highly integrated peripheral devices, as opposed to industrial computer systems, can greatly reduce the size and weight of equipment. High-level language has been widely used in the current DSP program development, making system development cycles significantly reduced.

Coprocessor, FPGA, has flexible design, high integration and logic control, etc. Besides that the powerful interface extensions and logic circuit processing can improve system performance. At last, the reconstruction of FPGA has greatly enhanced flexibility of hardware.

DSP+FPGA architecture can effectively compensate for the lack of a single CPU, making system more real-time and improving the efficiency of system.

Figure 4 shown the schematic diagram of digital galvanometer scanning system.

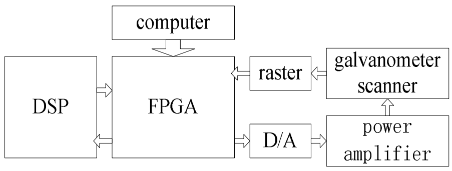

Figure 4. The schematic diagram of digital galvanometer scanning system

DSP will go through position-loop control and current-loop control algorithms and send the data to FPGA through the communication ports by the way of interruption handling. FPGA receives and outputs the data, through the D/A and the power amplifier, which control the movement of galvanometer.

A. Design of DSP

The system selects TMS320F28335, which is a floating-point controller produced by TI. The device has high precision, low cost, power consumption, high performance, highly integrated peripherals, data and program memory capacity, quick and accurate A/D converter and so on. It uses an 1.9V internal and 3.3V external power supply, and has up to 150MHZ clock, 32-bit CPU, using the Harvard pipeline, single-precision floating-point unit, rapid implementation capability of interrupt response, and a unified memory management model. It also can use language C/C++ to run the complex mathematical algorithm.

TMS320F28335, as the main controller, deals mainly with the coordinates of image sent by the host computer, while receiving grating position feeding back signal, then operates the closed-loop position control and current loop control algorithm.

TMS320F28335 hardware design in addition to completing the power, clock, and JTAG design, but also need to design the communication interface with PC.

The communication speed between PC and TMS320F28335 can meet the real-time data transmission requirement for laser marking system. USB1.1 has strong anti-interference ability and plug and play.

The system uses USB interface chip AN2131Q produced by Crypress, the highest speed up to 12Mbps. In order to improve data transmission speed, a FIFO chips is added between in AN2131Q and TMS320F28335, shown as Figure 5.

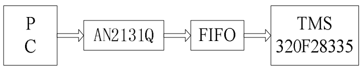

Figure 5. USB hardware design.

TMS320F28335 sends a negative pulse by changing control word to the AN2131Q and read the data. Timing diagram is shown in Figure 6.

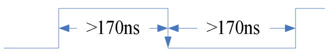

Figure 6. Timing diagram.

B. Design of FPGA

According to design requirements and cost, this design uses low-cost and highly integrated chip Ep2C5T144C7 produced by Altera. The chip with TQFP package contains 4608 LEs, 119,808 RAM bits, 13 embedded multipliers, 158 available I/O pins for users, and two PLLs.

Ep2C5T144C7, as a coprocessor, with a sufficient bandwidth, good stability, and taking up less CPU resources, achieves data buffering and simple treatment.

The hardware design of Ep2C5T144C7 contains power supply, clock, JTAG; D/A. DAC7744 is selected in system, because the chip has lower power, short setting time, and 16-bit monotonic performance.

EP2C5T144C7 is used for counting grating signals. Block diagram of FPGA is shown in Figure 7:

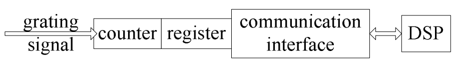

Figure 7. Block diagram of FPGA.

FPGA design focus on achieving the counting and storage of gating output signals, and timing match between the FPGA and DSP. The system gets the counter and register functions by compiling VHDL.

C. Communication

DSP and FPGA Communicate with each other through the control, data and address lines.

DSP controls the action of FPGA by changing the control words, reading or sending data, and changes the address to determine the location of the data.

IV. DESIGN AND SIMULATION OF CONTROLLER

In order to design galvanometer scanning system controller, firstly its mathematical model is established. The transfer function is the following equation. we can see galvanometer is second-order system.

$$G = \frac{\theta}{E} = \frac{K \ / \ R}{JS^2 + fs + g + \frac{KK_bS}{R}}$$

Where, θ is Angle of galvanometer, E is galvanometer input voltage, K is torque ratio of galvanometer coil, S is a complex variable in Laplace plane, J is moment of inertia, f is damping constant, g is coefficient of elasticity of torque rods, and K_b is back EMF constant.

Galvanometer scanning system is a closed-loop servo control system with high-speed and high-precision, so the system uses dual close-loop control structure. Correction of position loop improves steady state performance of the system, to achieve the high precision control. Correction of Current loop improves response speed of the system, to achieve the high-speed control.

Setting the transfer function of position loop correction is G_1, transfer function of current loop correction is G_2, the gain for the drive circuit is k_1, feedback factor of current loop is k_2, and feedback factor of position loop is k_3, the dual closed-loop control structure of galvanometer scanning system as shown in Figure 8：

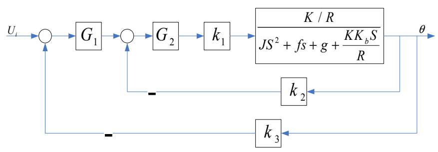

Figure 8. Dual closed-loop control structure of galvanometer scanning system.

Galvanometer scanning system is a control system with high-speed, high-precision and high repeatability, therefore requires more effective control algorithm than the traditional PID control algorithm. This paper presents a control algorithm, PID control algorithm with high-precision based on repetitive control compensation.

Repetitive control servo system applies to high-precision trajectory control. The input signal contains the error signal, adding a control deviation of the moment of previous cycle, after several cycles the tracking accuracy of system can be improved. This control method is suitable for tracking periodic signals, can also inhibit the periodic interference. In repetitive control, the general expectation of high frequency gain is reduced. Therefore, a low-pass filter control is added. The structure block diagram of galvanometer scanning system based on the algorithm is shown in figure 9:

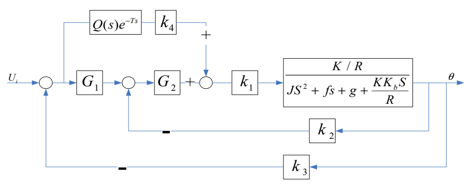

Figure 9. Block diagram of galvanometer scanning system based on repetitive control algorithm.

The simulation takes 6210 closed-loop moving magnet galvanometer as an example for simulation design. The main parameters are as follows: moment of inertia is 0.018gm * cm2, the torque coefficient is 27900dyne * cm / amp, the coil impedance is 3.72Ohms, coil inductance is

109μH, the back EMF is 48.7μV / ° / s, and RMS current is 2.4A.

In this paper, PID control algorithm and PID control algorithm with compensation based on repetitive control algorithm are simulated and compared in this system.

In Figure 10, simulation curve is the results of the step response for the system. The red curve represents the simulation curve of PID control algorithm with compensation based on repetitive control algorithm, and the blue one is the simulation curve of traditional PID control algorithm. Comparing the two curves, one can see that the rise time and settling time of the former simulation curve is shorter than the latter one and the overshoot is smaller. Thus we can get the conclusion that PID control algorithm with compensation based on repetitive control is better than traditional PID control algorithm, which is suitable for galvanometer scanning system for high-speed and high-precision control.

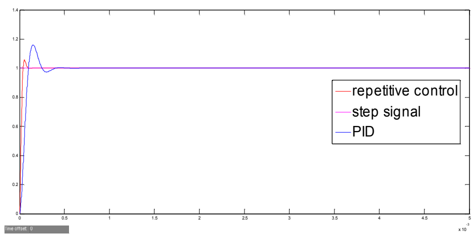

Figure 10. Simulation graph of the step response curve for galvanometer scanning system.

In Figure 11, graph is the response curve of sine for galvanometer scanning system. The red curve is the simulation curve of PID control algorithm with compensation based on repetitive control algorithm, the blue is the simulation curve of traditional PID control algorithm. Comparing two curves, one can see the tracking speed and precision of the former simulation curve is higher than the latter one, applying to galvanometer scanning system for high-speed and high repetitive control.

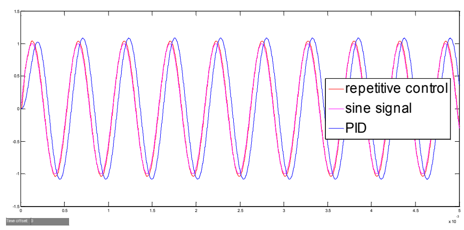

Figure 11. Simulation graph of the sine response curve for galvanometer scanning system.

V. SUMMARY

This paper focused on the design of digital galvanometer scanning system with high-speed and high-precision, discussed the operating principle of the composition of galvanometer and galvanometer scanning system, studied the hardware design and software algorithm of galvanometer scanning system with high-speed and high-precision, proposed hardware architecture based on DSP+FPGA and PID control algorithm with compensation based on repetitive control, and demonstrated the digital galvanometer scanning system with high-speed and high-precision is feasible through analysis and simulation.

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