FPGA-Based Multi-Axis Stepper Motor Control System Postprint

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Abstract

Advances in observation techniques and instrumentation are important means to propel solar physics research. Stepper motors are frequently employed as the driving source in precision structural adjustment components of various observation instruments, and the performance of stepper motor control systems directly affects the data accuracy and temporal resolution of solar telescopes. This paper introduces a multi-axis stepper motor control system independently developed by the Huairou Solar Observing Station. The system employs an FPGA as its core controller, utilizes interrupt handling mechanisms and input/output registers to generate multi-channel TTL square wave signals, and combines with drivers to achieve multi-axis stepper motor control; it shortens motor adjustment time through a periodic signal simplification processing algorithm; it employs Hall devices as position sensors to implement closed-loop control of the system, and improves signal recognition accuracy through software and hardware filtering of Hall signals; an onboard storage circuit is designed to save critical system parameters in real time, substantially enhancing overall system reliability. Additionally, the system is designed with abundant IO interfaces and communication interfaces, improving system integrability. Currently, the system has been deployed in multiple solar telescopes.

Full Text

Multi-axis Stepper Motor Control System Based on FPGA

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Abstract

Advances in observation technology and instrumentation are crucial means for advancing solar physics research. Stepper motors are frequently employed as the driving source for precision structural adjustment components in various observation instruments, and the performance of stepper motor control systems directly affects the data accuracy and temporal resolution of solar telescopes. This paper introduces a multi-axis stepper motor control system independently developed by the Huairou Solar Observation Base. The system employs an FPGA as the core controller, utilizes an interrupt processing mechanism and input/output registers to generate multiple TTL square wave signals, and combines drivers to achieve multi-axis stepper motor control. A periodic signal simplification processing algorithm is employed to shorten motor adjustment time. Hall devices are used as position sensors to implement closed-loop system control, and signal recognition accuracy is improved through software and hardware filtering of Hall signals. Onboard storage circuits are designed to save critical system parameters in real time, significantly enhancing overall system reliability. Additionally, the system features rich I/O interfaces and communication interfaces, improving system integrability. The system has currently been deployed in multiple solar telescopes.

Keywords: solar observation telescope; multi-axis stepper motor control; interrupt processing mechanism; closed-loop control; storage circuit

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Observation is the most important technical means in solar physics research. Since Galileo Galilei began using telescopes to observe sunspots in 1612, every innovation in solar observation instruments or technology has greatly advanced the progress of solar physics research [1]. The Huairou Solar Observation Station is one of the important observation bases of the National Astronomical Observatories, Chinese Academy of Sciences. Since its establishment in 1984, the Huairou base has become a world leader in the observational research of solar magnetic and velocity fields over the past 30 years [2][3][4]. During this period, the successful development of the solar magnetic field telescope and the multi-channel solar telescope [5] has significantly promoted the development of observational solar physics both domestically and internationally.

The main body of a solar telescope consists of three parts: the optical system, mechanical structure, and electronic system. To ensure high-quality telescope operation, the technical team at the Huairou Solar Observation Base has conducted comprehensive upgrades and transformations of the telescope by integrating advanced technologies [6][7]. The multi-axis stepper motor control system introduced in this paper is an important component of the telescope's electronic system.

Taking the Huairou multi-channel solar telescope as an example, the instrument employs 17 stepper motors as driving sources to precisely adjust the spatial positions of movable optical components in the filter and polarimetric analyzer, enabling measurement of polarization states at different wavelength magnetically sensitive lines. The accuracy, stability, and control efficiency of the stepper motor control system directly affect the precision and temporal resolution of solar magnetic field observation data.

The early stepper motor control architecture adopted by the Huairou base used a computer as the control core, integrated with digital I/O cards to generate control signals, combined with motor drivers to achieve precise stepper motor control [8]. The shortcomings of this design approach include: (1) high overall system complexity; and (2) weak system portability. To address these issues, the Huairou base developed a second-generation filter motor control system using embedded design concepts, significantly reducing dependence on computers. However, due to the integrated design of control and driver functions, the circuit had strong specificity and could not achieve universal control for different types of stepper motors. To compensate for the deficiencies of these two control systems, this paper proposes a new control strategy based on previous research. Specifically, an embedded system (FPGA) is used as the control core, combined with a computer and universal drivers to achieve multi-axis stepper motor control. The system design requirements are to reduce control system complexity while improving portability, stability, and expandability, while ensuring all control functional requirements for multiple stepper motors during solar telescope observation.

2 System Hardware Design

The overall structure of the multi-axis stepper motor control system introduced in this paper adopts a separated design (Figure 1 [Figure 1: see original paper]), mainly consisting of three modules: the host computer, controller, and driver. This separated modular design approach effectively reduces system coupling, improves portability, and enhances fault diagnosis efficiency. The motor controller is the main hardware design component of this system.

2.1 FPGA-Based System-on-Chip Construction

The Altera Cyclone IV E FPGA is used as the system-on-chip construction platform. This chip features 15,408 logic elements, 504 Kb of embedded memory, and 343 user I/O interfaces. The abundant logic resources and interface quantity provide hardware guarantee for multi-channel motor control. The NIOSII/e soft core is selected as the system' s embedded microprocessor. This processor uses a Harvard architecture with a maximum operating frequency of 100 MHz/s, and employs separate data and address buses. It can achieve optimal performance while occupying minimal logic resources. In addition to the processor, other Intellectual Property (IP) cores are added according to specific requirements to construct a complete system-on-chip. The IP core information and functions are shown in Table 1 .

Table 1 System-on-Chip IP Core Information

IP Core Information	Function
SDRAM Controller	Communicates with external SDRAM memory chip
EPCS Controller	Communicates with EPCS chip for program 固化, preventing loss during power failure
Interval Timer	Internal timer, used in this system to control TTL square wave signal frequency
PIO Core	Controls pin output levels for TTL square wave signal generation
UART Core	Communication chip driver, uses RS232 protocol for information interaction with host computer
SPI Bus Driver	Communicates with external ferroelectric memory chip designed for this system

2.2 Board-Level Hardware Circuit Design

System-on-chip construction belongs to the integrated circuit design domain, where the final design results are integrated into the chip. Due to certain limitations in its capabilities, peripheral support circuits must be designed to achieve signal level conversion and configuration information storage. The support circuits designed in this system can be functionally divided into the following sections:

1) **Serial Communication Circuit**: Uses standard RS232 serial circuit to implement information interaction of control instructions and status data with the PC.
2) **Control Signal Amplification Circuit**: Since FPGA pin output signals are 3.3V TTL level with voltage values that do not match the drivers, the 74HC245 chip is selected to amplify the control signals.
3) **Data Storage Circuit**: Uses ferroelectric memory FM25L256 to implement real-time storage of multi-channel stepper motor positions. The

memory uses the I2C bus protocol to connect with the system-on-chip, with communication rates up to 10 Mb/s, no read/write cycle limit, and data retention time of ten years in normal working environments.

4) **Signal Recognition Circuit**: Uses pull-up resistor design to enhance the transition signals generated by Hall sensors, enabling the PIO core in the system-on-chip to accurately identify edge transitions and enter the interrupt processing routine.

2.3 Controller Hardware Integration

The designed stepper motor controller hardware circuit is assembled and integrated (Figure 2 [Figure 2: see original paper]). The controller includes 48 signal output ports, 20 interrupt signal input ports, and 8 custom expansion ports. It can achieve synchronous control of up to 14 stepper motors.

3 System Software Design

To reduce system dependence on the PC and improve portability, this paper implements all functions including external signal recognition, control signal generation, data storage, position information feedback, and path optimization algorithms in the embedded software system design. This design approach reduces the complexity of PC-side software design and facilitates the design of the telescope' s autonomous observation control master system. Due to the extensive content of the embedded software system, this paper only introduces the key functional components.

3.1 Motor Control Signal Generation

The control signals required for a single stepper motor include: common signal (active high), direction signal, release signal (active low), and pulse signal (active on rising edge). The NIOSII soft core' s internal timer interrupt processing mechanism is utilized to change I/O register status values at equal intervals, generating TTL pulse level signals with a 50% duty cycle. The NIOSII modifies I/O register status values to generate the other three control signals.

The motor control signal software module is shown in Figure 3 [Figure 3: see original paper]. First, custom internal instructions are decoded. The decoded information includes motor number, rotation speed value, movement direction, and rotation step count. Based on the motor number information, the common terminal signal of the corresponding stepper motor is enabled, the release signal is pulled low, and the direction signal level value is set. Then, based on the rotation speed information, the initial value of the timer period register is set. The relationship between the register initial value and stepper motor rotation speed is as follows:

Where (rad/s) is the stepper motor rotation angular frequency, (steps/revolution) is the motor driver subdivision value, operating frequency (100 MHz), and is the register initial setting value. After completing the period setting, the timer is started. When an interrupt signal is generated, the program enters the interrupt function body, where the pulse signal port register status value is toggled to generate periodic TTL pulse signals. During the bandpass shifting process, the portion exceeding the rotating waveplate optical period (90°) undergoes a modulo operation, optimizing motor rotation control, reducing step count, and improving execution efficiency.

3.2 Position Information Storage

To improve the integration level of the embedded system, this paper adds external memory chips in the hardware design section to save stepper motor position information. The storage chip selected is the FM25L256 ferroelectric memory, which supports the SPI bus communication protocol with a memory array of 8-bit × 32,768 (256 Kbit). In the software design, a corresponding chip driver module is written to implement data read and write operations. The driver instruction consists of an 8-bit operation code, 16-bit address code, and data. Temporary data storage space must be allocated to hold read or write data. To facilitate calling by other functions, the driver code section is encapsulated as an independent module with corresponding data interfaces and operation mode interfaces. When stepper motor positions change, the new positions after change are stored. When the controller powers down and restarts, it automatically reads the position information saved before power loss. Additionally, other configuration information can be stored according to different project requirements, such as line center position information storage in filter control and constant-speed, fast, and slow speed value storage in equatorial axis control.

3.3 Position Signal Recognition

To achieve closed-loop control of stepper motors, Hall sensors are used to identify absolute positions (also called mechanical zero positions) to correct position errors generated during motor rotation. A Hall sensor is essentially a magnetic field sensor. When the magnet on the controlled mechanical structure moves into the recognition range, the Hall signal pin generates a high-to-low level transition signal. The NIOSII external interrupt mechanism is utilized to identify this transition signal and feed it back to the stepper motor control process. To improve signal recognition accuracy, filter code is added in software to eliminate interference signals generated by short-term strong magnetic fields or power supply voltage fluctuations.

4 Experimental Results

To verify the functional completeness, stability, and control accuracy of this design, the control system was applied to complete the design and upgrade of the multi-channel solar magnetic field telescope filter bandpass control system (17 motors). Related tests and verifications were conducted on the equipment after system replacement. Figure 4 [Figure 4: see original paper] shows the calibration measurement data of the line center position for the multi-channel telescope observation band. The horizontal coordinate in the figure represents the relative offset of the filter calibration position (Å), and the vertical axis represents the light intensity value received by the detector. The figure shows that the measurement curve has smooth intensity changes without single-stage waveplate (motor) control failure situations. The measurement curve has high consistency with solar spectral lines, achieving the bandpass shifting (multi-channel synchronous control) function. Figure 5 [Figure 5: see original paper] shows solar magnetic field measurement results at different wavelengths, demonstrating that the motor control system has achieved the control accuracy required by solar observation systems. Currently, the system operates stably and has undertaken related scientific observation tasks.

5 Conclusion

By employing programmable logic devices combined with IP soft cores and system-on-chip design concepts, a multi-axis stepper motor control system has been realized. During the research process, problems such as inaccurate signal recognition, data loss during power failure, and communication data loss were solved. The currently developed controller board can achieve closed-loop control of 12 stepper motors, and multiple controller boards can be used in parallel to reduce the overall volume of the control system. The system has been used to implement the filter bandpass control system design for the multi-channel solar telescope at the Huairou Observation Base (17 stepper motors), the filter bandpass control system design for the magnetic field telescope in Wenquan County, Xinjiang, and the equatorial axis control system design for the solar tower at Beijing Normal University.

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Key words: observation instruments; multi-axis stepper motor control; the interrupt processing mechanism; closed-loop control; external storage circuits.

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Note: Figure translations are in progress. See original paper for figures.