Design and Development of an Integrated Stepping Motor Drive and Control System for Nanoscale Positioning

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Abstract

To achieve low-cost automated control of nanoscale displacement, this paper proposes a precision motion control system driven by a stepping motor and guided by flexible hinges. For this purpose, an integrated stepping motor drive and control system has been designed and developed. With STM32F103C8T6 as the main control chip and DRV8825 as the driver chip, the system integrates the control module, drive module, power module, encoder module, strain feedback module and communication module, and cooperates with the host computer to achieve real-time precise control of the motor rotation angle and platform output displacement. This drive and control system features small size, low cost, simple wiring, and integration of the stepping motor control system driver and controller as well as nanoscale motion control.

Keywords

Nanoscale Positioning; Flexible Hinges; Stepping Motor; Integrated Drive and Control.

1. Introduction

With the development of science and technology, nanoscale displacement technology has become a key fundamental technology in micro/nano manufacturing, micro/nano detection, and micro/nano manipulation technologies. It has broad application prospects in fields such as ultra-precision machining, precision optics, and life sciences. Nanoscale displacement has become a hot topic of interest in current scientific research and industry [1].

Nanoscale displacement control systems typically use flexible hinges as guiding mechanisms and piezoelectric ceramic actuators as driving devices.Lining Sun et al. designed a two-dimensional micro-positioning stage driven by piezoelectric ceramics that achieved high positioning accuracy, but piezoelectric ceramics are expensive with high maintenance costs [2].To achieve low-cost micro/nanoscale displacement control, Qinghua Lu et al. studied a low-cost, high-precision micro-positioning platform driven by probe micrometers, pioneering a new approach for precision positioning technology [3];Stepping motors have advantages of simple structure, small size, low cost and high positioning accuracy. Combined with displacement reduction mechanisms based on flexible hinges, they can be used as the driving method for micro-positioning platforms [4]. However, traditional stepping motor control systems mostly use a separated structure where the controller and driver are two independent parts [5]. Such systems have a large size and complex wiring. At the same time, substantial wires are required between the controller and driver, which not only increases wiring difficulty, but also additional coupling paths for noise interference, reducing the system's immunity [6].

To solve the above problems, this paper designs and develops an integrated stepping motor drive and control system for nanoscale positioning. Through the integration design of the driver, controller, and detection device with shared resources and reduced connections, the size can be greatly reduced.

Compared with the traditional separated structure, this integrated design can reduce internal wire connections of the system, decrease noise interference, increase signal integrity, and thus significantly enhance the system's anti-interference capability and operational stability.

2. Overall System Design and Requirements Analysis

2.1 Overall System Design

The overall system design block diagram is shown in Figure 1, which contains host computer, drive & control board, linear stepping motor, flexible hinge displacement reduction device, strain feedback, etc. It is powered by a 24V DC switching power supply. The host computer sends control commands to the drive & control board to control the stepping motor to generate micron-level linear displacement, which pushes the flexible hinge displacement reduction device to produce nanoscale resolution displacement.To improve control accuracy, the rotary encoder feeds back stepping motor rotation angle signals, and the strain gauge feeds back flexible hinge deformation signals, forming a high-precision closed-loop control system.

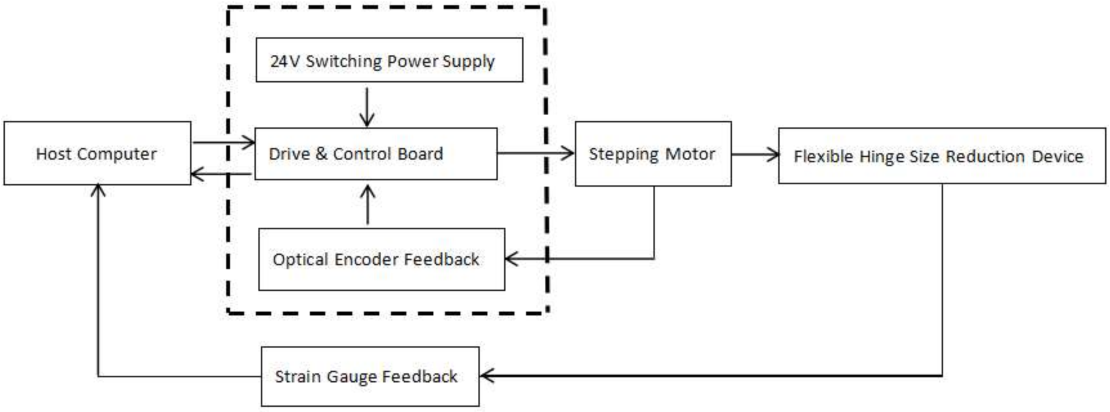

Figure 1. Overall System Design

2.2 Stepping Motor Drive Requirements Analysis

The integrated drive and control system for stepping motors consists of hardware components and software programs, which are complementary and essential [7]. The hardware comprises a power supply unit, motion controller, driver unit, communication interface, encoder module, and strain gauge feedback. r and syntax. The software part includes the stepping motor program and the host computer program, which cooperate with the host computer to achieve real-time control of the motor.

2.3 Flexible Hinge Strain Measurement Requirements Analysis

The displacement reduction mechanism based on a flexible hinge converts the micron-level displacement output of a linear stepper motor into nanometer-level displacement, while the flexible hinge acts as a guiding mechanism. Strain gauges are used for strain monitoring in the design, and high-precision positioning is achieved through closed-loop control.

3. System Hardware Circuit Design

3.1 Control Module Design

This design adopts a multi-level clock scheme with internal and external oscillators. Specifically, considering that the operating frequency of the main control MCU STM32 needs a higher frequency clock source for support, an 8MHz external crystal oscillator is used in the design to provide the main PLL clock. This 8MHz crystal is connected to the OSC_IN and OSC_OUT pins of the STM32 with resonant capacitors, which can generate an accurate and stable high frequency master clock. In addition, to allow the system to maintain RTC timing functions after entering low power mode, a 32.768kHz low frequency crystal oscillator is also used in the design, with its output connected to the dedicated RTC clock pin of the STM32, to provide a persistent low speed clock. Finally, the internal RC oscillator of the STM32 is also utilized to provide an auxiliary clock source for the system. By adopting this multi-level clock structure, the system ensures accurate high-speed operation while meeting the clock requirements of different modules, reliably guaranteeing the real-time control capability of the whole system.

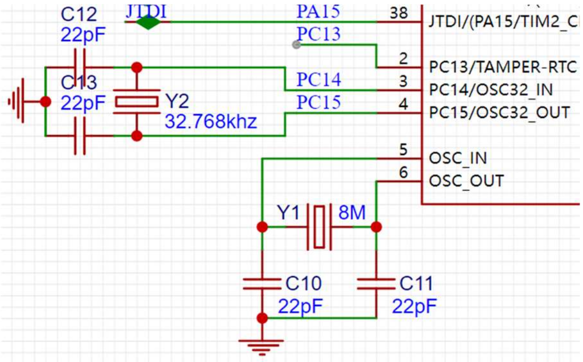

Figure 2. Clock Oscillator Circuit

3.2 Driver Module Design

The driver module uses the DRV8825 chip, which has over-temperature protection [11]. In the formulas below,PTOT is the total power dissipation,RDS(ON) is the resistance of each FET,IOUT(RMS) is the RMS output current applied to each winding.IOUT(RMS) is approximately 0.7 times the full scale output current setting. Since there are two motor windings, multiply by 4. At any time two fets conduct winding current for each winding (one high side and one low side). The maximum power dissipatable in the device depends on ambient temperature and heat sinking.

$$P_{TOT} = 4 \times R_{DS(ON)} \times \left(I_{OUT(RMS)}\right)^2 \tag{1}$$

AVREF and BVREF are the adjustment pins for the input current to the motor, and potentiometers are connected to them, with bypass capacitors in parallel, to adjust the motor voltage and thus adjust the current [12]. The maximum is 2.5A.

$$\mathrm{I} = \frac{\mathrm{VREF}}{5\mathrm{R}11} \tag{2}$$

When using the motor, the start speed needs to be configured properly. If the target motor start speed is too high, the motor will not rotate.f_{step} is the Start speed, v is the Motor speed, n_m is the Microstep level, θ_{step} is the Step angle[12].

$$f_{step}(\mu steps/second) = \frac{v(\frac{rotations}{minute}) \times 360(\frac{\circ}{rotation}) \times n_m(\frac{\mu steps}{step})}{60(\frac{seconds}{minute}) \times \theta_{step}(\frac{\circ}{step})} \tag{3}$$

MODE0, MODE1, MODE2 are the microstep pins, which can provide 5 microstep modes of 1/2, 1/4, 1/8, 1/16, 1/32;DIR is the direction input pin, which can change the rotation direction of the stepper motor through code, connected to pin PB8 of the STM32F103C8T6 control chip;NENBL is the enable pin, which is the control signal input, connected to pin PB9 of the STM32F103C8T6 control chip. It is normally high level active, and the chip can only work normally when this pin is activated. When nENBL is low, the H-bridge output is enabled and rising edges on the STEP pin are recognized.When nENBL is high, the H-bridge is disabled and the outputs are in a high-impedance state, ignoring STEP inputs.nRESET is the reset pin which resets the chip to its initial state. It is tied in parallel with the sleep pin nSLEEP and connected to VCC_3.3V through R14.STEP is the signal input pin, which can adjust the stepper motor through software programming and quickly and easily change the position of the stepper motor to achieve precise control. It is connected to pin PA8 of the STM32F103C8T6 control chip.When nSLEEP is low, it puts the device into a low power sleep state. In this state:

- The H-bridge is disabled
- The gate drive charge pumps are stopped
- The V3P3OUT regulator is disabled
- All internal clocks are stopped

In this sleep state, all inputs are ignored until nSLEEP returns high.So in summary, pulling nSLEEP low disables the chip and puts it into a low power sleep mode. The chip will not respond to any inputs until nSLEEP is brought high again. This sleep mode can be used to reduce power consumption when the motor is not being driven.When waking up from sleep mode, there should be a delay of around 1ms before applying STEP inputs to allow internal circuits to stabilize.

nFAULT is the fault pin. It will trigger overcurrent protection when the output current exceeds the chip's rated operating current, lighting up the fault LED. It is powered by VCC_3.3V and connected to fault LED LED5.

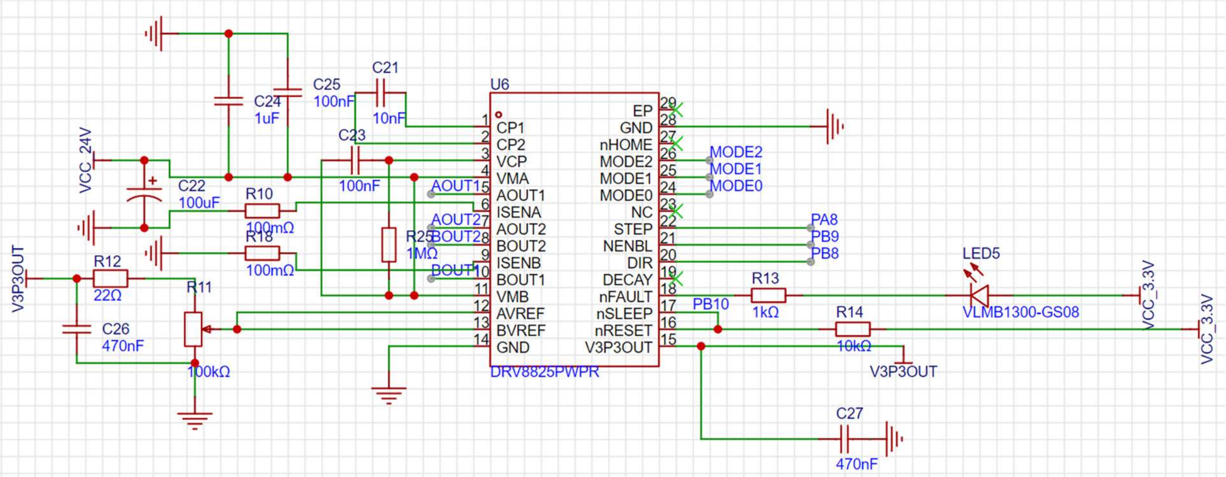

Figure 3. Drive Module Circuit

3.3 Module Design

This design adopts a two-stage power conversion architecture to achieve distributed power supply from 24V to 3.3V. The first stage power conversion uses a DC-DC module to step down from 24V to 5V. The second stage power conversion then uses the BL1117 linear regulator to convert 5V to 3.3V. This two-stage conversion approach not only achieves higher conversion efficiency, but also provides a stable power supply with low ripple noise for the components [13].

3.4 Communication Module Design

The internal communication of the system is mainly the information interaction between the STM32F103C8T6 control chip and the DRV8825 driver chip. The STM32F103C8T6 control chip sends signal commands to control the DRV8825 driver chip to send pulses to the stepper motor, achieving precise control of the stepper motor.

The external communication includes program burning and information interaction between the drive control board and the host computer. The program is burned into the STM32F103C8T6 control chip through computer software, achieving software and hardware integration, and completing the control of the drive module.

3.5 Encoder Module Design

This design uses an optical encoder as the feedback method. An NPN optocoupler chip is used, which consists of a light emitting diode and a phototransistor. The main working principle is to use the light emitting diode to convert the input current into visible or infrared light, which is then converted back into an electrical signal by the photosensitive transistor after being received. This achieves optical coupling and electrical isolation between the input and output.

4. PCB Design

The PCB size is 91mm×95mm, which is compact and reflects the integrated, miniaturized features. Figure 4 shows the actual PCB.

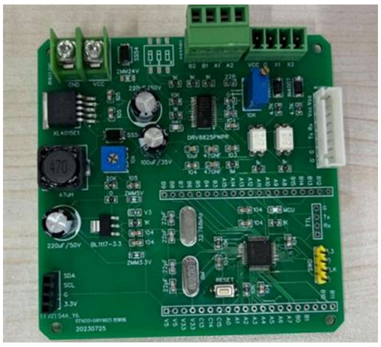

Figure 4. Actual PCB

5. System Software Design

Based on the software requirements for the integrated stepper motor drive and control system, a modular design approach is adopted to divide the software system into three main parts: initialization module, motor control module, and communication module.The initialization module plays a crucial role in properly starting up the system by configuring and initializing the STM32 MCU and related hardware components.The motor control module ensures stable system operation. The communication module enables internal data exchange within the system as well as communication with the external host computer. It is used to send control commands and feedback operational status.

6. Conclusion

The main work of this paper is the design of an integrated stepper motor drive and control system oriented towards nano-positioning, which achieves integration of the driver and controller in a stepper motor control system. The system requirements are analyzed, and the flexible hinge, hardware circuit design and software design are completed. The drive and control board has a small size, low cost, and simple wiring, realizing the integration of the driver and controller in the stepper motor control system as well as nano-motion control.

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