

Design of an STM32-Based Adjustable Constant-Temperature Filter Wheel Box Postprint

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Abstract

To meet the observation requirements of scientific targets for the 1.2m telescope astronomical imaging system, a temperature-adjustable constant-temperature filter wheel box based on STM32 control was designed. The wheel box contains three wheels, which can rotate cooperatively under the drive of their respective motors to achieve automatic switching of up to 15 filters. To ensure the stable operating wavelength of the filters, the wheel box incorporates a thermal insulation system based on a PID temperature control algorithm to maintain the interior of the wheel box at the set temperature. The host computer can communicate commands with the electronic control box via serial port, and the electronic control box directly drives the wheel motors and heating/thermal insulation. The entire system features a compact structure, good electronic control safety, and complete microcontroller program functionality. Final tests demonstrate that the wheel box can operate normally at low temperatures of -25°C , maintain temperature within $\pm 1^{\circ}\text{C}$ of the target temperature in constant temperature mode, exhibit stable performance during long-term operation, and complete a filter switch in less than 10 seconds.

Full Text

Design of a Programmable Thermostatic Filter Wheel Box Based on STM32

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Abstract: To meet the observational requirements of scientific targets for the 1.2m telescope astronomical imaging system, we designed a programmable thermostatic filter wheel box controlled by an STM32 microcontroller. The box contains three wheels that can rotate cooperatively under individual motor drives, enabling automatic switching among up to 15 filters. To ensure stable operating wavelengths, the wheel box incorporates a thermal management system based on a PID temperature control algorithm to maintain the interior at a set temperature. The host computer communicates with the electronic control box via serial port, which directly drives the wheel motors and heating system. The entire system features a compact structure, safe electronic control, and comprehensive microcontroller program functionality. Testing demonstrates that the wheel box operates normally at low temperatures down to -25°C , maintains temperature within $\pm 1^{\circ}\text{C}$ of the target in constant-temperature mode, exhibits stable performance during long-term operation, and completes each filter switch in under 10 seconds.

Keywords: Filter switching; STM32; Temperature control algorithm; Motor driving

Classification: TP232

The accretion process of supermassive black holes and their co-evolution with host galaxies are fundamental questions in black hole physics and galaxy formation and evolution. Active Galactic Nuclei (AGN) represent the phase of rapid supermassive black hole growth, characterized by high luminosity, multi-wavelength continuum radiation, and strong emission lines. Both the continuum and emission lines exhibit varying degrees of variability, with optical-UV broad emission line variations primarily excited by continuum changes. By measuring the response time delay of AGN broad emission lines to continuum variations, we can determine the distance of the line-emitting gas from the central black hole (reverberation mapping). Combined with spectroscopically measured line velocity widths, this allows estimation of the central black hole mass. Traditional reverberation mapping relies primarily on long-term spectroscopic monitoring of AGN targets. However, due to spectrograph efficiency limitations, this approach requires large-aperture telescopes, is time-consuming, and suffers from low calibration precision.

To achieve high-efficiency, high-precision reverberation mapping, the University of Science and Technology of China developed a 1.2m telescope astronomical imaging system that primarily utilizes multi-band photometry with broad- and narrow-band filters to monitor continuum and emission line variability in AGN. This system is expected to increase the reverberation mapping sample size by a factor of four and substantially expand the parameter space coverage by including more high-luminosity, high-redshift AGN targets.

Achieving this scientific goal requires monitoring a batch of AGN over long periods (months to years) with overall photometric precision better than 1%,

imposing stringent requirements on the filters. In particular, the center wavelength of the system's narrow-band filters drifts with temperature. The structure and optical path of the 1.2m telescope astronomical imaging system are shown in [Figure 1: see original paper]. This is a red/blue dual-channel imaging system. The telescope receives incident light at $f/8.429$, which passes through a collimating system to become parallel beams. A beam splitter then separates the light into red and blue channels: the red channel is transmitted with wavelength range 650–1000 nm, while the blue channel is reflected with wavelength range 400–650 nm. The beams then pass through the filter system, with each channel requiring replacement of up to 14 filters. The narrow-band filters have bandwidths ranging from 8–17 nm. After filtering, the parallel beams enter the imaging system with focal ratio $f/5$ before being imaged by the camera.

The narrow-band filters used in the system are highly sensitive to temperature due to their small bandwidth. We characterized their performance using a self-built filter testing system to observe temperature-induced drift in bandwidth and center wavelength. As shown in [Figure 2: see original paper], within the 10–23°C temperature range, center wavelength drift is negligible, while bandwidth increases at lower temperatures. Over the tested $\Delta 13^\circ\text{C}$ range, bandwidth changes by approximately 0.03 nm, representing about 0.2% of the total bandwidth. However, at typical high-altitude observatory sites with large environmental temperature variations, the annual nighttime temperature difference can reach 40°C, with winter day-night differences of 15–20°C. Estimating based on an annual nighttime temperature span of 40°C, the bandwidth variation would reach 0.6%. Therefore, effective temperature control is crucial for high-precision narrow-band photometry. In addition to temperature control, rapid real-time filter switching is also important for certain scientific targets requiring simultaneous or quasi-simultaneous multi-band photometric monitoring.

To address these requirements, this paper presents the design of a programmable thermostatic multi-wheel filter wheel box system based on STM32 control, which ensures filter temperature stability while enabling fast, stable switching among 14 filters. This system is also applicable to other optical systems requiring rapid switching and temperature control.

1 System Architecture

The filter wheel architecture is identical for both red and blue channels in the telescope imaging system. As shown in [Figure 3: see original paper], the system consists of three components: the wheel box, electronic control box, and host computer. The wheel box motors and heating elements are driven by the control box, while the wheel box provides real-time position and temperature feedback signals to the control box. The control box comprises a main control board and motor driver board, interfaces directly with the wheel box, and receives/responds to host computer commands via serial port.

The mechanical structure of the wheel box [5] is illustrated in [Figure 4: see

original paper]. The box contains three filter wheels, each driven by an independently controlled stepper motor. Each wheel has six apertures that can accommodate up to five filters using filter holders, with one remaining empty aperture. When a filter from a particular wheel needs to be placed in the optical path, the other two wheels align their empty apertures with the path, ensuring only one filter is in the beam at any time. Each aperture has a position sensor tab: apertures with filters have one tab, while the empty aperture has two tabs to distinguish it as the HOME position. These tabs work with position sensors on the wheel box housing to determine the current wheel position, which is fed back to the control box through an interface. Motor control is handled by the motor driver and control boards within the control box. The wheel box interior is lined with heating elements and temperature sensors, which together with corresponding modules in the control box form the temperature control system.

The electronic control box serves as the low-level hardware control module, consisting of a motor driver board and microcontroller main board housed in a compact enclosure. It communicates with the host computer via serial port. Users can operate the system through host software to configure filter selection, start/stop temperature control, obtain real-time temperature and wheel position information, and confirm temperature and wheel status. In debug mode, users can also set target temperature, control individual wheel rotation and homing, adjust temperature control parameters, configure motor step angles, calibrate filter positions, and set the mapping between wheel apertures and filter bands.

2 Control Circuit

The filter wheel control circuit architecture is shown in [Figure 5: see original paper], comprising a main control board and motor driver board housed together in the control box, with only external interfaces exposed for sensors, control, communication, and power. The control box handles communication with the host computer and implements low-level control and data acquisition for the filter wheel box motors and temperature control. The main control board performs temperature control and generates motor control signals, while the driver board converts these signals into two-phase signals that directly drive the motors.

The main control board is the core of the electronic control module, implementing wheel motor control and filter thermal management according to host commands. It includes the STM32 main controller, serial communication module, temperature control module, and motor control module. The STM32 microcontroller is a 32-bit device based on the Cortex-M3 core with sufficient general-purpose I/O, on-chip USART serial transceivers, and SPI interfaces.

In the motor control module, control signals from the main board to the driver board undergo level shifting via transistors. Position sensor signals from inductive proximity sensors on the wheel box are input to the STM32 through optocouplers for level shifting and protective isolation.

The temperature control module includes temperature acquisition and MOSFET drive output. We selected a 24-bit high-precision ADC for temperature measurement, which features a built-in current source and uses four-wire measurement to cancel lead resistance effects on RTD (resistance temperature detector) measurement accuracy. Heating element control passes through a digital isolator and driver chip, then drives a P-channel power MOSFET to provide PWM current to the heating elements lining the wheel box interior.

Precise wheel rotation requires stepper motor drives. Considering maximum synchronous torque, holding torque, minimum step angle, and cost, we selected Oriental Motor CMK243MAP two-phase stepper motors with a basic step angle of 0.9° . While these motors include driver boards, using separate drivers for each of the three motors per wheel box would result in excessive volume and redundant control structure. Therefore, we integrated three motor drivers onto a single driver board that converts three channels of control signals from the main board into three channels of direct motor drive signals, enabling compact co-location with the control board.

The driver board operates on 24V and 3.3V power supplies, with 24V provided by the main board and 3.3V generated from 24V via an LDO. Control signals from the main board pass through optocouplers for electrical isolation before reaching the motor driver chips, enhancing interface safety. The DRV8825 motor driver chip is a bipolar stepper motor driver capable of maximum 2.5A output, though only 0.6A is needed to drive the wheel motors. It features an on-chip microstepping indexer configurable up to 32 microsteps, achieving 12,800 steps per revolution and improving filter switching precision.

The entire electronic design emphasizes electrical isolation and safety. Optocouplers and digital isolators insulate high-power or high-voltage modules from low-voltage main control circuits to prevent external shorts from damaging the main chip. The design is compact and small-volume, with one control box per wheel box for convenient installation and removal. Subsequent experiments demonstrated that the electronic control module can reliably implement the required functions.

3 STM32 Firmware Program Design

The STM32 microcontroller handles generation of motor control signals and heating element control signals, as well as parsing of host commands. The firmware structure is shown in [Figure 6: see original paper] and includes initialization, command parsing, status query, ADS1248 temperature measurement, PWM heating control, motor control, position sensor, parameter modification/read, and serial communication modules.

Upon power-up, the microcontroller executes a series of initializations including system clock, GPIO, serial port, interrupts, motor control timers, heating element driver timers, temperature sampling ADC configuration, and initial states for motors and heaters. The microcontroller receives commands via

serial port, processes them through the command parsing module, and triggers other functional blocks. The basic command format is: “>Command-Word(+Space+Parameter)#”, where “>” is the start character that validates the following command word, and “#” is the end character indicating command completion. Major commands are listed in , covering basic system functions accessible to users.

The wheel motor control flow is shown in [Figure 7: see original paper]. The 15 filter apertures in the three wheels are numbered 1-15. When commanded to switch to a specific filter, the program determines the required aperture for each wheel. For example, to switch to filter #8, the program controls wheels 1 and 3 to their empty apertures while wheel 2 rotates to its third filter aperture. If this is the first operation after power-up, the program first drives each wheel to its HOME position for reset before moving to the target position; otherwise, it moves from the current position. Each filter position has a sensor tab that triggers an interrupt, incrementing the current position register until the target filter is reached. Since sensor tabs trigger over a range near the sensor, precise filter positioning requires an additional small offset correction beyond the trigger position. These correction values were experimentally calibrated for each filter position. After reaching the target, the program stops the motor and updates the system status.

Motor operation follows the S-shaped acceleration curve shown in [Figure 8: see original paper], where acceleration gradually increases then decreases to prevent step loss from sudden starts or stops. The program accelerates the motor every 5 ms, requiring 500 ms from start to constant speed, with PWM pulse frequency increasing from 1.5 kHz to a stable 25 kHz while maintaining 50% duty cycle.

The temperature control flow is shown in [Figure 9: see original paper], employing a PID (Proportional-Integral-Derivative) algorithm—a common feedback control method. When the microcontroller receives a command to set a target temperature, each system cycle polls the temperature control module and enters the PID control function to calculate: the temperature error e (current minus target), the integrated error $ie = ie + e$, and the derivative error $de = e - e$ (where ie and e are previous values). The P value is computed as:

$$P = kp \times e + ki \times ie + kd \times de$$

The algorithm then checks if $p > MAX_duty_cycle$ or $p < 0$, outputting the corresponding limit; otherwise, the duty cycle equals p . MAX_duty_cycle is set to 85%. To achieve smooth temperature rise and stable maintenance at the target, the three parameters kp , ki , and kd must be tuned. The proportional coefficient kp determines rise speed; the integral coefficient ki amplifies accumulated error over time, determining post-target oscillation; the derivative coefficient kd suppresses error. In practice, the first two terms dominate. Experimental tuning determined optimal values of $kp = 10$ and $ki = 0.02$, ensuring adequate heating speed while minimizing overshoot and oscillation. The program adjusts PWM duty cycle to p once per second for continuous heating power control. Temper-

ature stability is declared when the temperature remains within $\pm 2^{\circ}\text{C}$ of the target for over 100 seconds.

The entire program leverages the STM32 firmware library for easy peripheral utilization and rapid application development. The design was compiled using the Keil Vision5 development platform and flashed to the STM32 via STLINK.

4 Test Results

After completing the design, we tested the filter wheel box performance. [Figure 10: see original paper] shows a photograph of the wheel box during testing. Building upon successful single-filter switching, we used a script to send random filter-switching commands to the control box continuously for 24 hours. The system demonstrated excellent stability: a single wheel rotating at constant speed takes approximately 1.4 seconds per aperture; the maximum switching time (when all three wheels must travel the maximum allowed distance of five apertures) is about 10 seconds.

Additionally, we wrapped the filter wheel box in thermal insulation and placed it in a freezer set to -25°C to simulate actual low-temperature environments, with a target temperature of 20°C . Testing showed the wheel box heating elements could reach the target temperature in approximately 2.5 hours. The heating curve is shown in [Figure 11: see original paper]. Under PID control, the heating element drive PWM initially outputs at the maximum 85% duty cycle for maximum power. As temperature approaches the target, the proportional term $k_p \times e$ dominates initially, causing duty cycle to decrease linearly with error e . As the ratio between proportional and integral terms decreases, the integral term dominates, providing just enough power to maintain temperature without oscillation.

[Figure 12: see original paper] shows temperature variation over time from two PT100 sensors inside the wheel box after reaching stability at room temperature. Since the PT100s measure internal air temperature rather than temperature at the heating elements, they exhibit some lag in response to heating power changes, limiting control precision. However, measured temperature fluctuations remain within $\pm 1^{\circ}\text{C}$, which is sufficient for requirements.

This paper presents a compact thermostatic filter wheel box system that can hold up to 15 filters internally, with functions including motor drive, temperature control, and status monitoring implemented by an STM32-based control system. A series of tests demonstrated excellent system performance, and it has been operating stably in the 1.2m telescope system at the Delingha Astronomical Observatory. This design provides a valuable reference for other optical systems requiring filter switching.

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

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