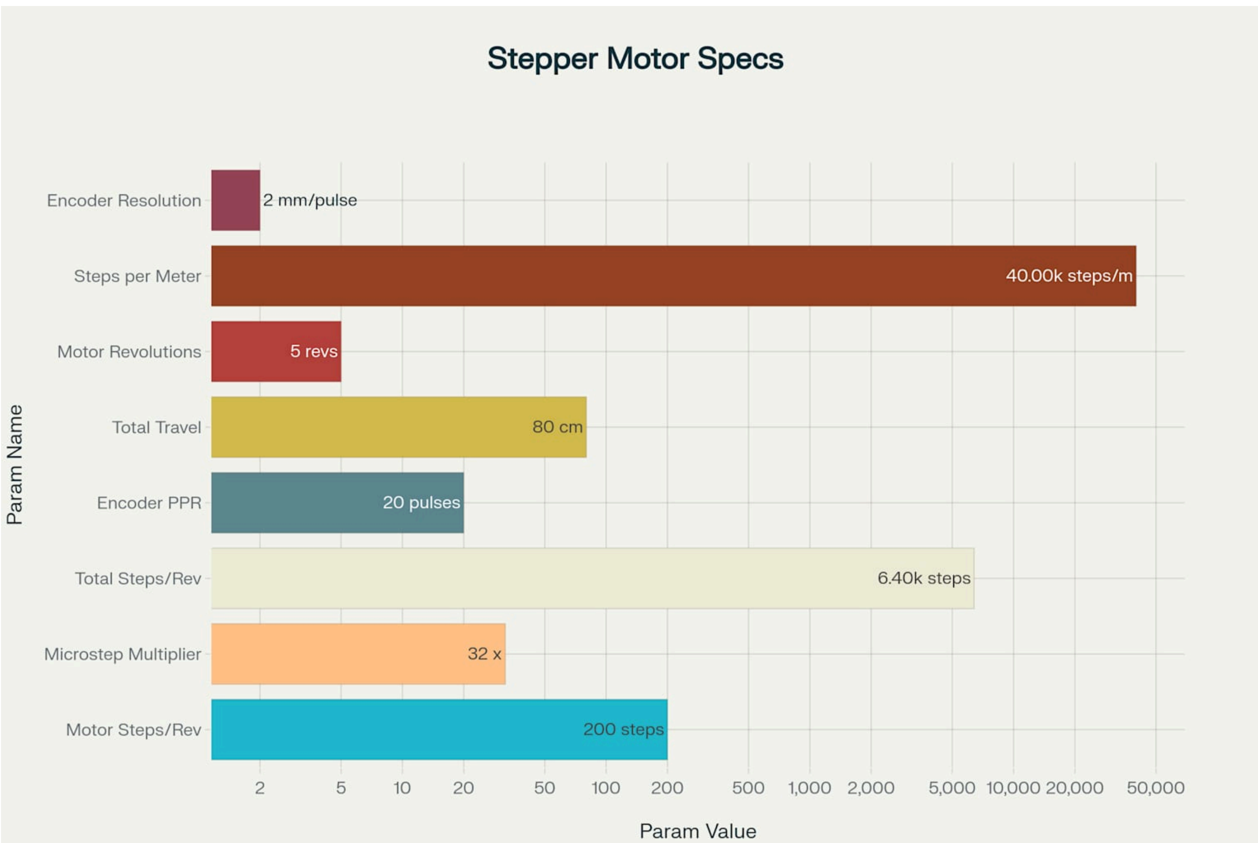
Comprehensive Analysis: Closed-Loop Stepper Motor Control System

System Overview

This code implements a sophisticated **closed-loop stepper motor control system** with optical encoder feedback for precise positioning and motion control. The system combines traditional open-loop stepper control with closed-loop feedback to achieve high accuracy and reliability in industrial automation applications.



System Specifications - Stepper Motor Control Parameters

1. Systematic Step-by-Step Code Explanation

Hardware Configuration

The system uses a **TB6560 stepper driver** with **1/32 microstepping** controlling a **200-step/revolution stepper motor**. The mechanical setup includes:

- **Total system travel**: 80cm in 5 motor revolutions
- **Gear ratio**: 4:1 (motor to encoder wheel)

- **Optical encoder**: 20 pulses per revolution
- **System resolution**: 40,000 steps per meter
- **Encoder resolution**: 2mm per pulse

Software Architecture

The program follows a **state machine architecture** with multiple operating modes:

Setup Phase:

1. **Serial Communication**: Initializes at 115,200 baud for user interface
2. **GPIO Configuration**: Sets up step/direction pins, limit switches, and encoder interrupt
3. **Stepper Initialization**: Configures AccelStepper library with driver mode
4. **Interrupt Setup**: Attaches encoder interrupt to GPIO pin 2 for real-time feedback
5. **Variable Initialization**: Sets up timing, PID parameters, and mode flags

Main Loop Execution:

1. **Serial Input Processing**: Handles user commands and mode selection
2. **Switch State Management**: Reads and debounces limit switches every 50ms
3. **Encoder Calculations**: Updates position, velocity, and acceleration from encoder feedback
4. **PID Control Execution**: Applies closed-loop correction when enabled
5. **Mode Execution**: Runs the currently selected operating mode
6. **Stepper Operation**: Executes single step using AccelStepper library
7. **Real-time Display**: Updates position and motion data every 100ms

Encoder Feedback System

The encoder system provides **real-time position verification** through:

- **Interrupt-driven counting**: Triggered on rising edge of encoder signal
- **Direction detection**: Based on stepper motor speed
- **Velocity calculation**: Using position change over time with 5-point moving average
- **Acceleration calculation**: Derived from velocity change

PID Control Implementation

The PID controller provides **closed-loop position correction** with:

- **Error calculation**: Difference between commanded and actual position
- P **Proportional term**: Immediate response to current error
- I **Integral term**: Eliminates steady-state error
- **Derivative term**: Reduces overshoot and oscillation

D

- **Output limiting**: Prevents excessive corrections that could cause instability

2. Working of the Code

Operating Modes

Mode 1: Acceleration Mode

- Tests motor acceleration capabilities with real-time feedback
- User inputs: target velocity (m/s) and acceleration rate (m/s^2)
- Monitors position error throughout acceleration and travel
- Provides return-to-start capability with encoder verification

Mode 2: Constant Velocity Mode

- Validates steady-state velocity control accuracy
- Input range: 0.001 to 15.0 m/s
- Uses 2x acceleration ramp for smooth velocity transitions
- Compares commanded vs actual velocity using encoder feedback

Mode 3: Calibration/Homing Mode

- Establishes absolute position reference using limit switch
- Moves at slow speed (5cm/s) toward home position
- Resets both stepper and encoder positions to zero
- Moves to start position (2.5cm offset) for operational readiness

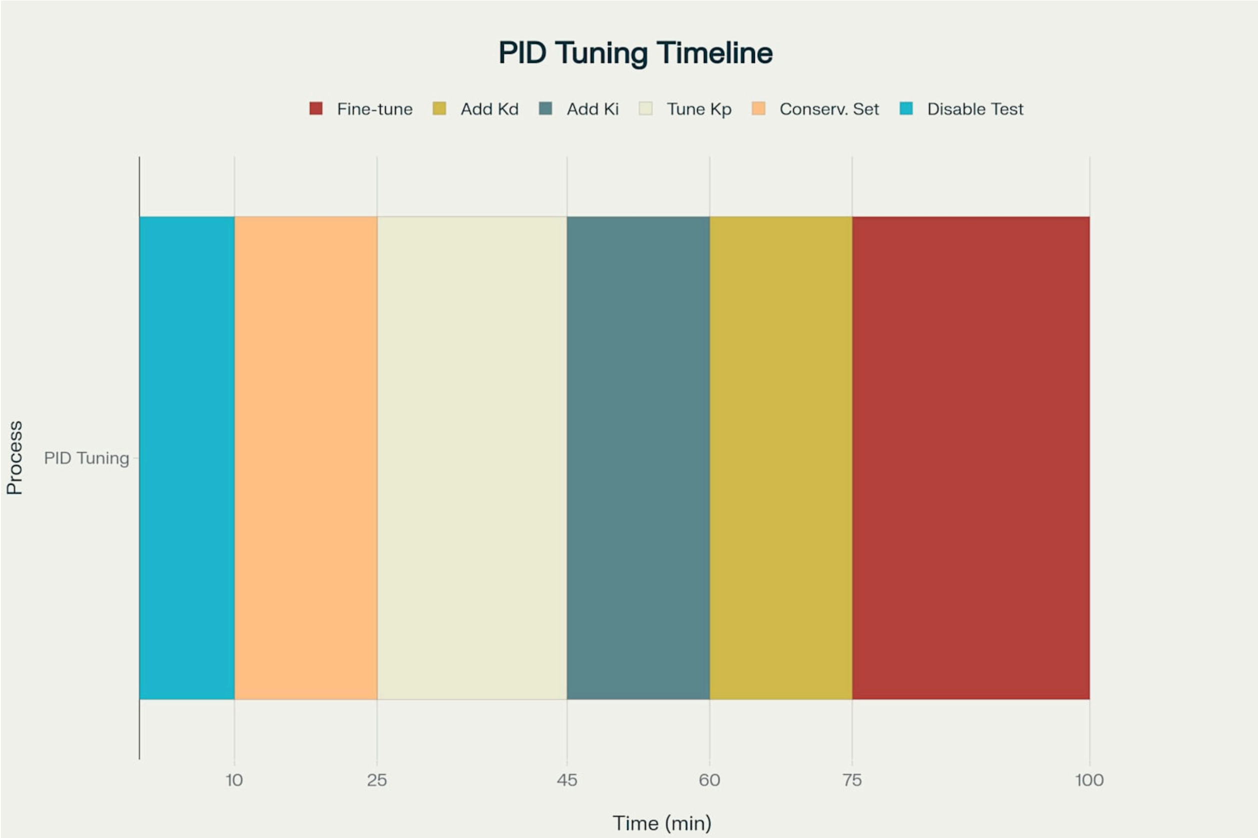
Mode 4: Trapezoidal Motion Mode

- Implements advanced motion profile with three phases:
  - **Acceleration phase**: Ramp up to cruise speed
  - **Cruise phase**: Maintain constant velocity
  - **Deceleration phase**: Controlled slowdown to stop
- Validates motion profile feasibility before execution
- Provides smooth, controlled motion for precision applications

Safety Features

- **Dual limit switches**: Home switch and right safety switch
- **Emergency stop**: Immediate halt on "stop" command
- **Timeout protection**: 30-second limit for homing operations
- **Debouncing**: 50ms debounce delay prevents false triggering
- **Position limiting**: Software prevents travel beyond physical limits

3. PID Tuning Steps for Calibration



PID Tuning Process Timeline - Systematic 6-Step Procedure

Systematic Tuning Procedure

Step 1: Baseline Testing (10 minutes)

- Disable PID control using `'pid off'` command
- Run constant velocity test to establish open-loop performance
- Record steady-state position error and system behavior
- This provides baseline for improvement measurement

Step 2: Conservative Initial Settings (15 minutes)

- Set initial parameters: Kp=1.0, Ki=0.0, Kd=0.0
- Use commands: `'kp 1.0'`, `'ki 0.0'`, `'kd 0.0'`
- Test with small movements to ensure stability
- Verify basic closed-loop operation without oscillation

Step 3: Proportional Gain Tuning (20 minutes)

- Gradually increase Kp until system begins to oscillate
- **Critical point**: Note the oscillation threshold
- Reduce Kp to 50-70% of oscillation point for stability margin

- Test across different velocities to ensure consistent performance
- **Typical range**: 0.5 to 5.0 depending on system dynamics

Step 4: Integral Term Addition (15 minutes)

- Start with Ki = Kp/10 as initial estimate
- Gradually increase Ki to reduce steady-state error
- **Warning**: Stop if system becomes unstable or oscillates
- Monitor for integral windup in saturated conditions
- **Typical range**: 0.01 to 0.5

Step 5: Derivative Term Optimization (15 minutes)

- Begin with Kd = Kp/100 as starting point
- Increase Kd to reduce overshoot and improve settling time
- **Caution**: Watch for high-frequency noise amplification
- Balance between damping and noise sensitivity
- **Typical range**: 0.001 to 0.1

Step 6: Final Validation and Testing (25 minutes)

- Test all operating modes with tuned parameters
- Verify stability across different speeds and accelerations
- Check response to external disturbances
- Document final parameters for future reference
- **Acceptance criteria**: Position error < 2mm, no oscillation

Performance Monitoring

The system provides real-time feedback during tuning:

- **Position error**: Displayed in millimeters
- **Velocity tracking**: Encoder vs commanded velocity
- **Acceleration profile**: Real-time acceleration display
- **PID output**: Internal correction values

4. Sample Tests for Debugging and Verification

Initial System Verification

Hardware Checks:

```
1. Power supply voltage verification
2. Stepper motor wiring continuity
3. Encoder signal integrity (oscilloscope recommended)
```

```
4. Limit switch operation (manual test)
5. All connection security checks
```

Software Validation:

```
1. Serial communication at 115,200 baud
2. Encoder interrupt triggering verification
3. Switch debouncing functionality
4. PID parameter initialization
5. System constant calculations accuracy
```

Functional Test Suite

Test 1: Basic Movement Verification

- **Setup**: Select constant velocity mode
- **Input**: 0.05 m/s velocity
- **Expected**: Smooth 80cm travel in 16 seconds
- **Verification**: Encoder count increases proportionally
- **Pass criteria**: Position error < 5mm

Test 2: Encoder Accuracy Validation

- **Setup**: Move exactly 20cm distance
- **Calculation**: Expected encoder pulses = 20cm ÷ 0.2cm = 100 pulses
- **Measurement**: Compare actual vs expected count
- **Pass criteria**: ±2 pulses tolerance

Test 3: PID Response Verification

- **Setup**: Enable PID with `'pid on'`
- **Test**: Run acceleration mode with real-time monitoring
- **Observation**: Position error should decrease during motion
- **Pass criteria**: No sustained oscillation, error < 2mm

Test 4: Safety System Validation

- **Setup**: Manually trigger limit switches during operation
- **Expected**: Immediate motor stop and position reset
- **Verification**: System returns to safe state
- **Pass criteria**: Response time < 100ms

Advanced Performance Testing

Test 5: Speed Accuracy Assessment

- **Setup**: 0.1 m/s constant velocity over 40cm
- **Expected**: 4.0 second travel time
- **Measurement**: Encoder-based speed calculation
- **Pass criteria**: ±5% speed accuracy

Test 6: Acceleration Profile Verification

- **Setup**: 0.05 m/s² acceleration to 0.1 m/s
- **Expected**: 2.0 second acceleration time
- **Monitoring**: Real-time velocity display
- **Pass criteria**: Smooth acceleration curve

Test 7: Trapezoidal Motion Validation

- **Setup**: 10cm accel, 10cm decel, 60cm cruise at 0.1 m/s
- **Verification**: Three distinct motion phases
- **Measurement**: Encoder position tracking
- **Pass criteria**: Smooth transitions between phases

Test 8: Repeatability Assessment

- **Setup**: Multiple homing cycles (minimum 10)
- **Measurement**: Home position consistency
- **Pass criteria**: ±0.5mm repeatability

Troubleshooting Guide

Problem: Encoder Not Counting

- Check encoder power supply (3.3V or 5V)
- Verify interrupt attachment to GPIO 2
- Test signal quality with oscilloscope
- Check for loose connections or damaged cables

Problem: Large Position Errors

- Inspect mechanical system for backlash
- Verify gear ratio calculations in code
- Check for missed steps (insufficient current)
- Recalibrate encoder resolution constant

Problem: Motor Oscillation

- Reduce PID gains systematically
- Check for mechanical resonance frequencies
- Increase derivative term to add damping
- Verify encoder signal quality and noise levels

Problem: Inconsistent Homing

- Adjust switch debouncing parameters
- Check switch wiring and connections
- Reduce homing speed for better accuracy
- Verify switch mounting and alignment

System Acceptance Criteria

A fully functional system must meet these specifications:

- **Position Accuracy**: ±2mm throughout travel range
- **Velocity Accuracy**: ±5% of commanded speed
- **Repeatability**: ±1mm for repeated movements
- **Homing Accuracy**: ±0.5mm home position consistency
- **Response Time**: < 100ms for safety stop
- **Stability**: No oscillation during steady-state operation

This comprehensive control system provides industrial-grade precision with robust safety features and extensive diagnostic capabilities for demanding automation applications.

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