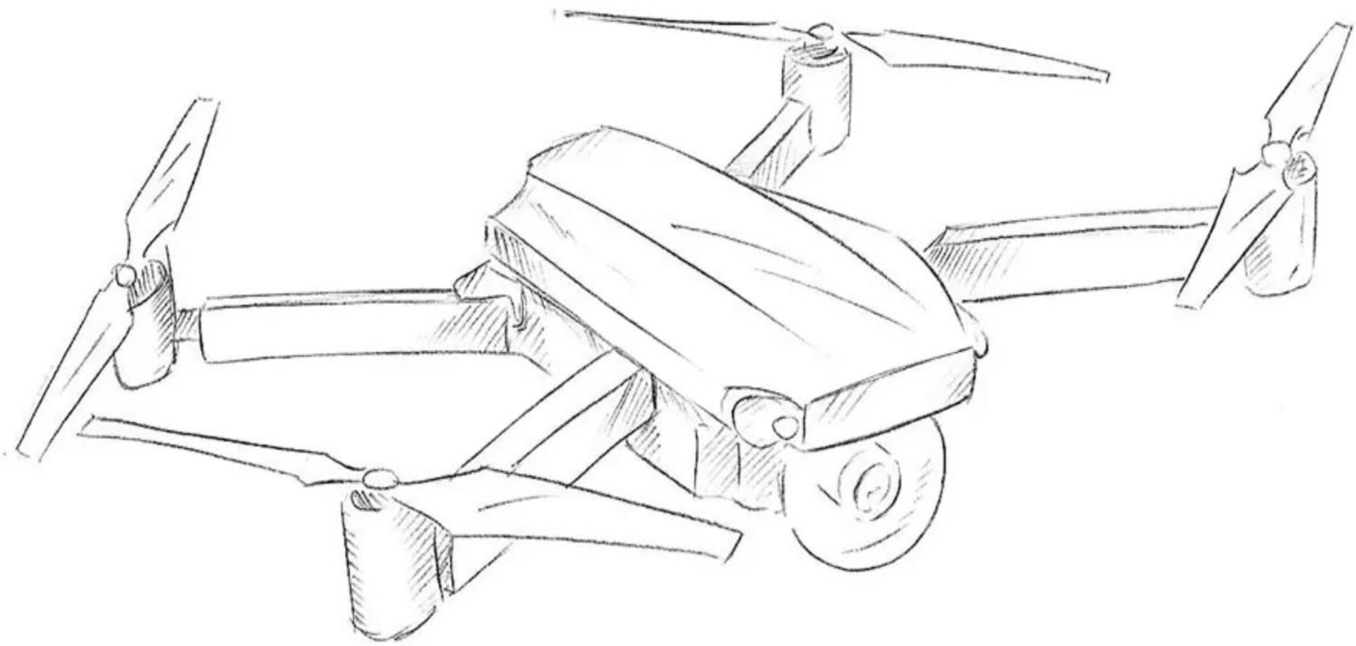
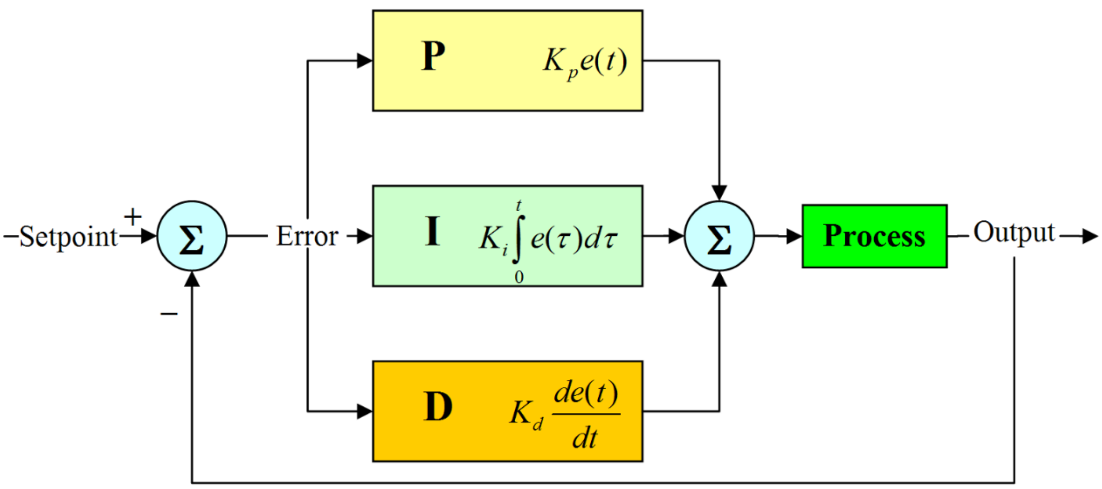
Hardware Engineer's Guide

PID CONTROL





By Shimi Cohen

1. PID FUNDAMENTALS

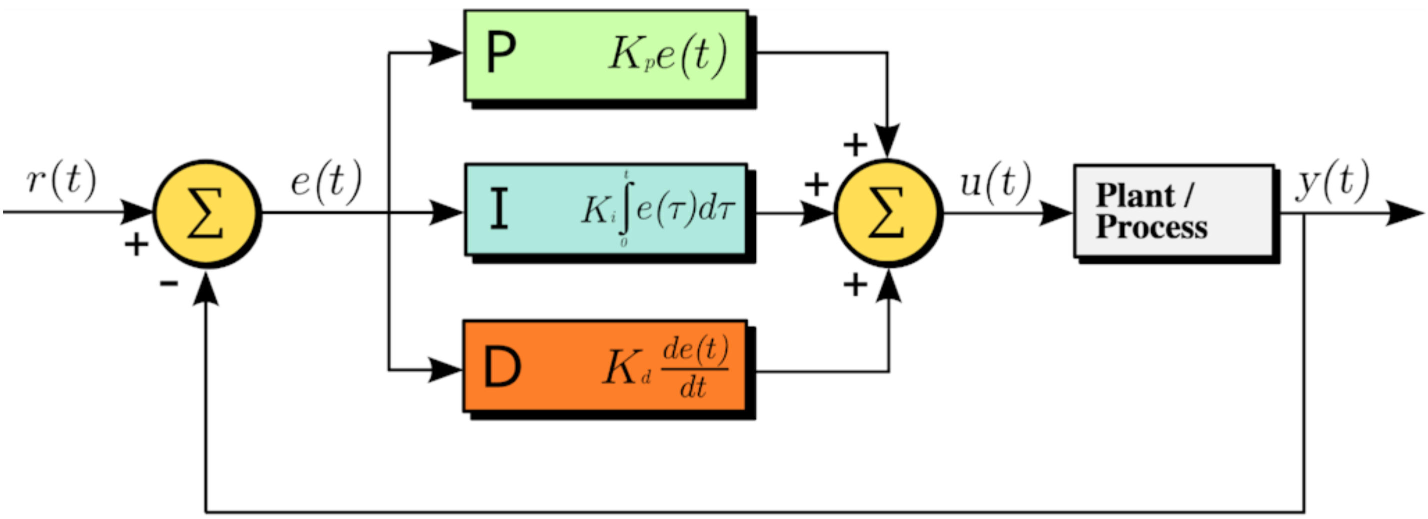
PID FOUNDATION

TRANSFER FUNCTION

$$G(s) = Kp + Ki/s + Kd \cdot s$$

COMPONENT	TIME DOMAIN	FREQ. DOMAIN	PHYSICAL EFFECT
Proportional	$Kp \cdot e(t)$	Kp	Immediate response strength
Integral	$Ki \cdot \int e(t)dt$	Ki / s	Historical error elimination
Derivative	$Kd \cdot de(t)/dt$	Kd · s	Predictive overshoot prevention

Term	Analogy	Too Low	Too High
P	*Immediate reaction to difference.*	*Slow*	*Unstable.*
I	*Corrects for past errors, accumulated drift*	*Slow Settle*	*Overshoots*
D	*Anticipates changes, smooths approach*	*Overshoots*	*unstable*



1.1 PROPORTIONAL CONTROL (P-TERM)

CORE FUNCTION

Direct multiplication of current error by gain factor.

- Immediate Response: Output changes instantly
- Linear Relationship: Doubling error doubles control output
- Steady-State Error: Always present in **pure proportional**
- Stability Margin: Higher Kp lower stability but faster response
- Response time: Instantaneous
- Steady accuracy: Limited by proportional band
- Typical Kp range: 0.1 to 100 (application dependent)

P

1.2 INTEGRAL CONTROL (I-TERM)

CORE FUNCTION

Accumulates historical error to eliminate steady-state offsets.

- Error Accumulation: Continuously sums past errors over time
- Offset Elimination: Forces steady-state error to zero
- Wind-up Susceptibility: Can saturate during large transients
- Stability Impact: Reduces phase margin, can cause oscillation
- Continuous: True integration for analog systems
- Discrete: Trapezoidal rule for digital implementation
- Wind-up protection: Essential for practical systems

I

1.3 DERIVATIVE CONTROL (D-TERM)

CORE FUNCTION

Provides predictive action based on error rate of change.

- Predictive Nature: Responds to error rather than magnitude
- Overshoot Reduction: Opposes rapid changes in error signal
- Noise Amplification: High-frequency noise becomes dominant
- Damping Enhancement: Improves transient response characteristic
- Pure derivative: unusable due to noise amplification
- Low-pass filtering: Typically 10:1 to 100:1 ratio
- Kick suppression: required for setpoint changes

D

2. THE PLANT

The object being manipulated (Heater, Valve, Motor etc.)

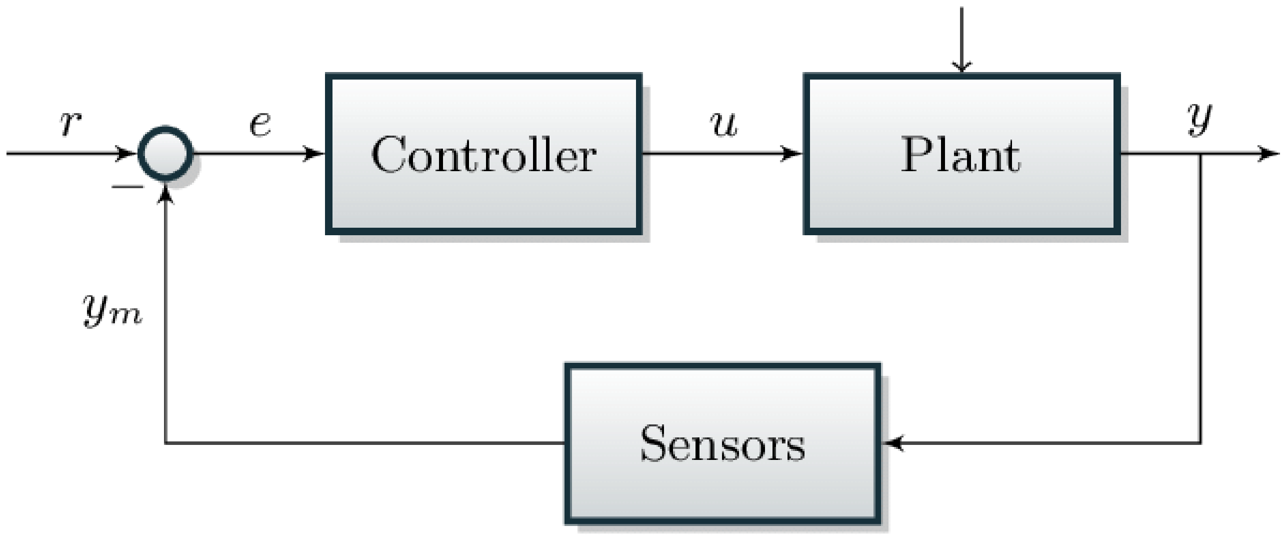
2.1 TIME CONSTANTS AND DELAYS

TIME CONSTANT

- Thermal Systems: Heat capacity / thermal conductance
- Mechanical Systems: Inertia / damping coefficient
- Electrical Systems: L/R or RC time constants
- Process Systems: Volume / flow rate relationships

DEAD TIME EFFECTS

- Transport delays: Physical distance between control and measurement
- Processing delays: Computational and signal processing time
- Sensor delays: Measurement device response time



2.2 NON-LINEARITIES AND CONSTRAINTS

COMMON NON-LINEAR ELEMENTS

NON-LINEARITY	EFFECT ON CONTROL	COMPENSATION METHOD
Saturation	Output limiting	Anti-windup, gain scheduling
Dead zone	Poor small-signal response	Bias injection, dither
Backlash	Oscillation tendency	Pre-loading, feed-forward
Rate limiting	Slow large-signal response	Acceleration limiting

CONSTRAINT HANDLING

- Actuator saturation: 0-100% valve, ±10V amplifier limits
- Rate constraints: Maximum slew rate limitations
- Physical limits: Temperature, pressure, position boundaries

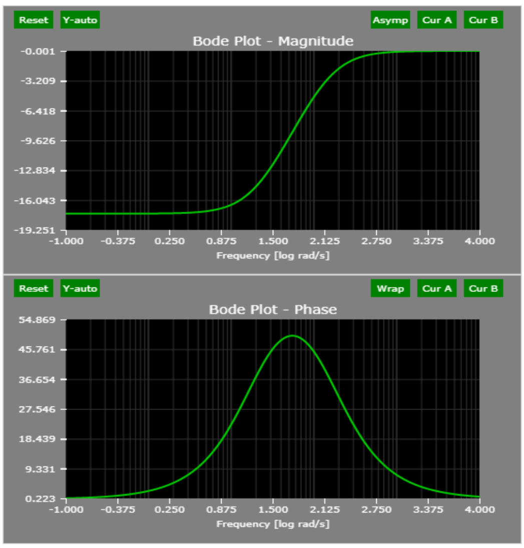
2.3 SYSTEM IDENTIFICATION TECHNIQUES

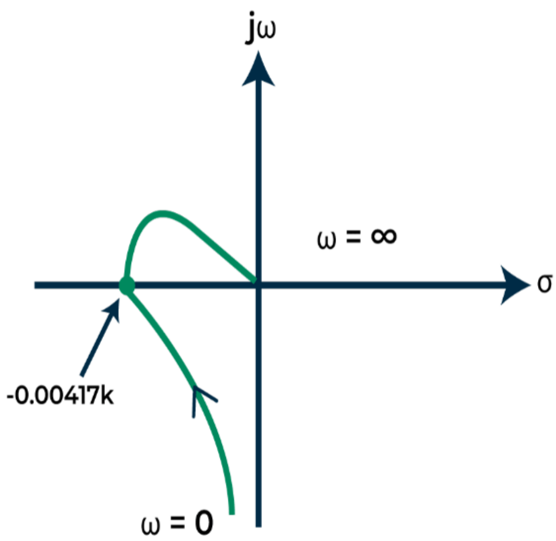
STEP RESPONSE ANALYSIS

- Rise time: 10% to 90% of final value
- Settling time: Within 2% of final value
- Overshoot: Peak value above final value
- Time constant: 63% of final value time

FREQUENCY RESPONSE METHODS

- Bode plot analysis
- Nyquist criteria





3. FEEDBACK PATH

3.1 SENSOR TECHNOLOGIES BY APPLICATION

POSITION/DISPLACEMENT SENSORS

SENSOR TYPE	RESOLUTION	ACCURACY	BANDWIDTH	TYPICAL APPLICATIONS
Encoder	0.1° - 0.001°	±0.05°	10kHz	Servo positioning, robotics
Resolver	0.1°	±0.02°	1kHz	Harsh environment motors
LVDT	0.1μm	±0.1%	1kHz	Precision linear positioning
Hall Effect	1°	±1°	100kHz	Low-cost positioning

TEMPERATURE SENSORS

SENSOR TYPE	RANGE	ACCURACY	RESPONSE	INTERFACE
Thermocouple	-200°C : 1800°C	±0.5°C	100ms	Differential voltage
RTD	-200°C : 850°C	±0.1°C	1s	Resistance measurement
Thermistor	-50°C to 300°C	±0.05°C	10ms	Resistance measurement
IC Sensor	-40°C to 125°C	±0.25°C	1ms	Voltage/digital output

3.2 SIGNAL CONDITIONING REQUIREMENTS

AMPLIFICATION AND SCALING

- Sensor output range: mV to V
- ADC input range: Typically, 0-3.3V
- Gain calculation: (ADC_range) / (Sensor_range)
- Offset compensation for bipolar signals

NOISE REJECTION TECHNIQUES

- Differential signaling for long cable runs
- Shielding and grounding for electromagnetic immunity
- Low-pass filtering at sensor interface
- Digital filtering for software-based noise reduction

3.3 SENSOR PLACEMENT AND CALIBRATION

CRITICAL PLACEMENT CONSIDERATIONS

- Thermal coupling: Sensor proximity to controlled element
- Mechanical coupling: Rigid mounting for position feedback
- Electrical isolation: Avoiding ground loops and interference
- Environmental protection: Temperature, vibration, moisture

CALIBRATION PROCEDURES:

- Zero-point calibration at known reference
- Span calibration using full-scale reference
- Linearity verification across operating range
- Temperature compensation coefficient determination

3.4 ERROR DETECTION AND PROCESSING

ERROR SIGNAL GENERATION

$$Error = Setpoint - Process\_Var$$

ERROR SIGNAL CONDITIONING:

- Scaling: Engineering units to controller units
- Limiting: Prevent excessive error signals
- Rate limiting: Prevent derivative kick
- Filtering: Remove high-frequency noise

MULTIPLE INPUT HANDLING:

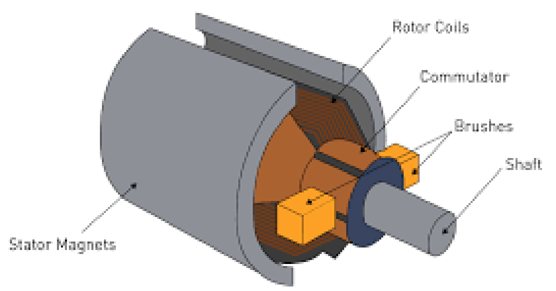
- Sensor redundancy for critical applications
- Fault detection through signal comparison
- Automatic sensor switching for failures
- Signal validation and range checking

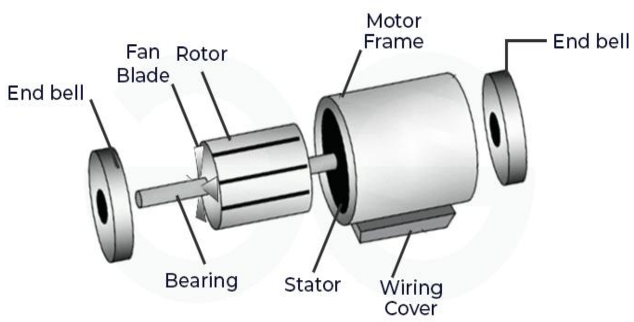
4. FORWARD ARCHITECTURE

4.1 ACTUATOR INTERFACE DESIGN

POWER STAGE CLASSIFICATIONS

ACTUATOR TYPE	POWER STAGE	CONTROL SIGNAL	PROTECTION REQUIRED
DC Motor	H-Bridge PWM	PWM + Direction	Current limiting, thermal
AC Motor	3-Phase Inverter	3-Phase PWM	Over-current, over-voltage
Servo Valve	Linear Amplifier	±10V Analog	Short-circuit, thermal
Heater	SSR/Contactor	On/Off or PWM	Over-temperature, earth fault





4.2 CURRENT LIMITING AND PROTECTION

CURRENT SENSING METHODS

- Shunt resistors: High accuracy, low cost
- Hall effect sensors: Isolated, wide bandwidth
- Current transformers: AC systems, isolation
- Integrated current sensing: Motor drivers

PROTECTION IMPLEMENTATION

- Hardware current limiting: Independent of software
- Thermal monitoring: Junction and case temperature
- Over-voltage protection: Surge suppressors, TVS diodes
- Under-voltage lockout: Prevent malfunction at low supply

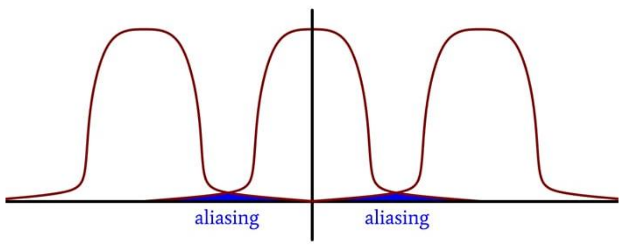
5. SIGNAL PROCESSING

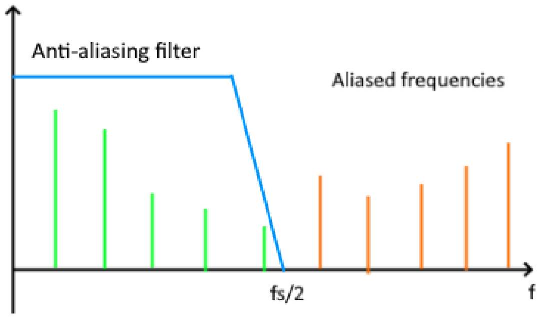
5.1 ANTI-ALIASING AND NOISE REJECTION

ANTI-ALIASING FILTER DESIGN

Sampling Rate Selection:

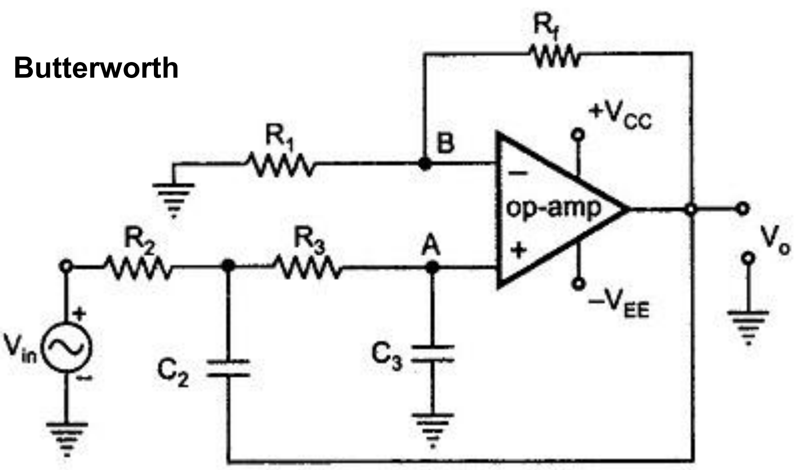
- Nyquist criterion: $fs > 2 \times fmax$
- Practical rule: fs = $10 \times control\ bandwidth$
- Oversampling benefits: Reduced filter requirements





FILTER TOPOLOGIES

FILTER TYPE	ORDER	ROLL-OFF	GROUP DELAY	APPLICATION
Butterworth	2nd-8th	-40dB/decade	Moderate	General purpose
Bessel	2nd-6th	-40dB/decade	Linear	Pulse response
Chebyshev	2nd-8th	-60dB/decade	Non-linear	Steep cutoff
Elliptic	4th-8th	-80dB/decade	Non-linear	Minimum order



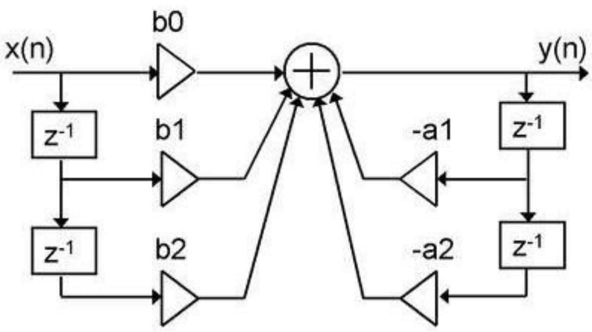
5.2 BIQUAD FILTER STRUCTURES

DIGITAL BI-QUAD IMPLEMENTATION

$$H(z) = (b0 + b1 \times z^{-1} + b2 \times z^{-2}) / (1 + a1 \times z^{-1} + a2 \times z^{-2})$$

Coefficient Calculation Methods:

- Bilinear transform: Frequency warping compensation
- Matched Z-transform: Impulse response matching
- Zero-order hold: Step response matching



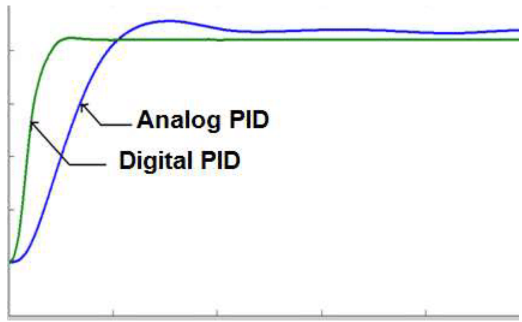
5.3 DIGITAL VS ANALOG FILTERING

ANALOG FILTER ADVANTAGES

- No sampling limitations
- Inherent anti-aliasing
- Lower group delay
- Simpler implementation

DIGITAL FILTER ADVANTAGES

- Programmable coefficients
- Perfect repeatability • Complex transfer functions
- No component drift

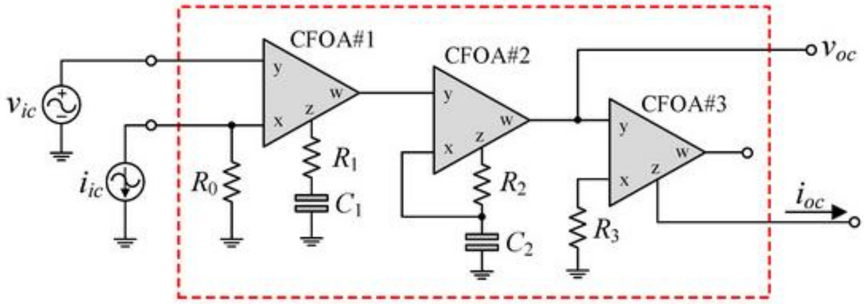


6. PID IMPLEMENTATION

6.1 ANALOG PID

CLASSIC ANALOG PID CONFIGURATION

- OPAMP: High slew rate, low offset drift
- Resistors: 1% tolerance, low temperature coefficient
- Capacitors: Low leakage, stable dielectric
- Power supplies: Low noise, good regulation



6.2 DIGITAL PID

FIXED-POINT VS FLOATING-POINT

Fixed-Point Advantages:

- Faster execution on most microcontrollers
- Deterministic execution time
- Lower power consumption
- Suitable for real-time applications

Floating-Point Advantages:

- Wider dynamic range
- Simpler coefficient calculation
- Reduced scaling concerns
- Better for complex algorithms

NUMERICAL PRECISION REQUIREMENTS

- Control output: 12-16 bits typical
- Internal calculations: 24-32 bits recommended
- Overflow protection: Essential for integral term

6.3 MCU INTEGRATION

TIMER CONFIGURATION:

- Control loop timing: Hardware timer interrupt
- PWM generation: Dedicated PWM peripherals
- ADC sampling: Synchronized with control loop
- Communication: Non-blocking for real-time operation

6.4 EMBEDDED SYSTEM OPTIMIZATION

REAL-TIME PERFORMANCE

- Fixed execution time: Avoid conditional branches in ISR
- Memory allocation: Static allocation only in ISR
- Stack usage: Monitor stack depth for nested interrupts
- Priority levels: Control loop highest priority

CODE OPTIMIZATION TECHNIQUES:

- Table lookups: Replace calculations with lookup tables
- Bit manipulation: Use shifts instead of multiply/divide
- Compiler optimization: Enable appropriate optimization levels
- Assembly critical sections: Hand-optimize time-critical code

7. TUNING & TROUBLESHOOTING

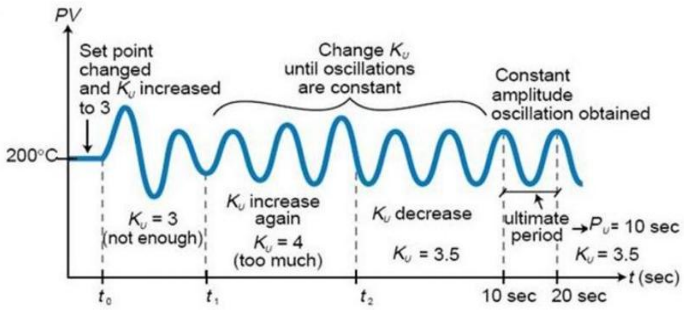
7.1 PRACTICAL TUNING METHODS

ZIEGLER-NICHOLS METHOD

Critical Gain Determination

- Set Ki = 0, Kd = 0
- Increase Kp until sustained oscillation occurs
- Record critical gain (Kc) and oscillation period (Tc)

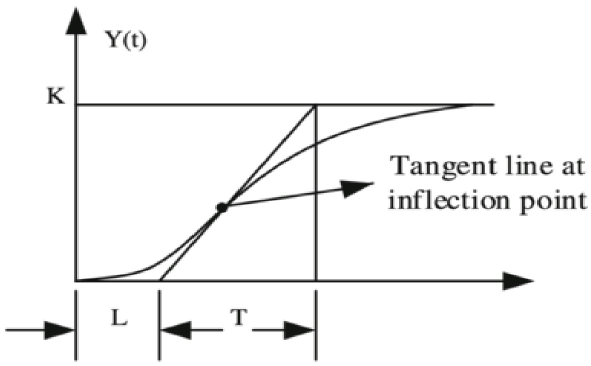
TYPE	KP	KI	KD
P-only	0.5 × Kc	0	0
PI	0.45 × Kc	1.2×Kp/Tc	0
PID	0.6 × Kc	2×Kp/Tc	Kp × Tc/8



COHEN-COON METHOD

Based on open-loop step response characteristics:

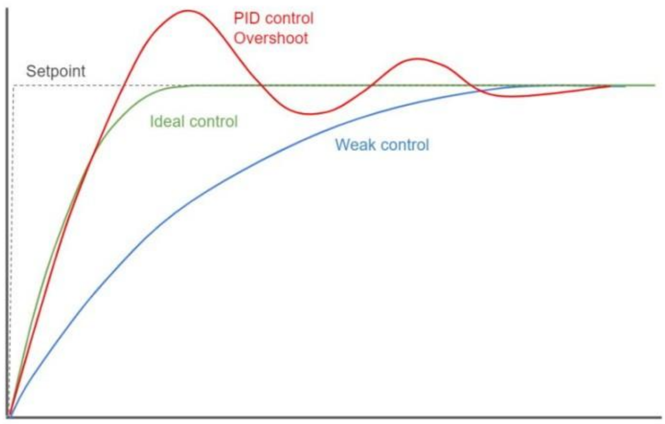
- Process gain (K): Steady-state output change / input change
- Time constant (τ): Time to reach 63% of final value
- Dead time (θ): Time before response begins



7.2 COMMON FAILURE MODES AND SOLUTIONS

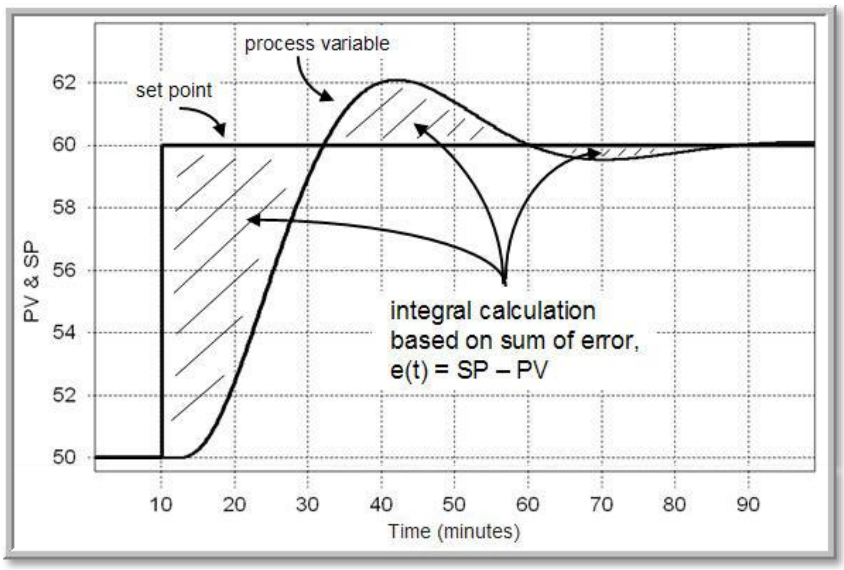
OSCILLATION PROBLEMS

TYPE	CHARACTERISTICS	ROOT CAUSE	SOLUTION
High Freq	Small Amp, fast	D gain too high	Reduce Kd or add filter
Mid Freq	Growing Amp	P gain too high	Reduce Kp
Low Freq	Large Amp, slow	I gain too high	Reduce Ki
Limit	Square wave	Actuator saturation	Reduce gains, add anti-windup



INTEGRAL WINDUP PREVENTION

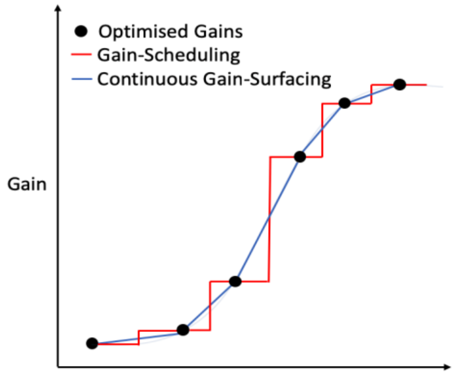
- Conditional integration: Stop integration when output saturated
- Back-calculation: Reduce integral term when output limited
- Clamping: Limit integral term to prevent excessive accumulation



7.3 ADVANCED TUNING TECHNIQUES

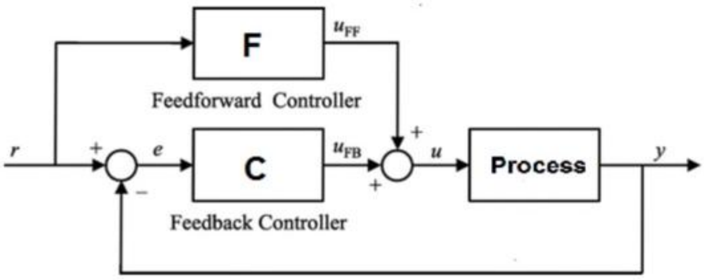
GAIN SCHEDULING

- Multiple PID parameter sets for different operating regions
- Smooth transitions between parameter sets
- Based on setpoint, process variable, or external conditions



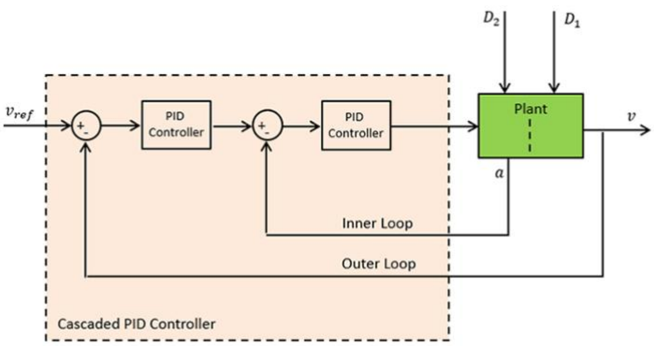
FEED-FORWARD CONTROL

- Anticipate disturbances before they affect process variable
- Reduce dependency on feedback for known disturbances
- Combine with PID for optimal performance



CASCADE CONTROL

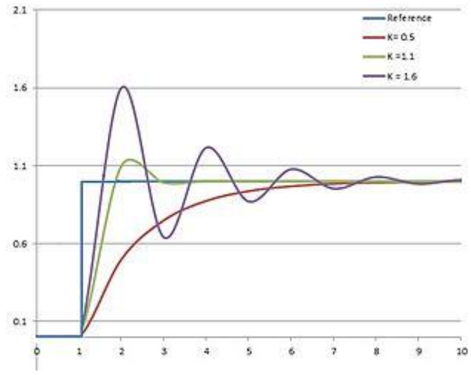
- Inner loop: Fast variable (current, pressure)
- Outer loop: Slow variable (position, temperature)
- Improved disturbance rejection and stability



7.4 SYSTEM IDENTIFICATION FOR BETTER TUNING

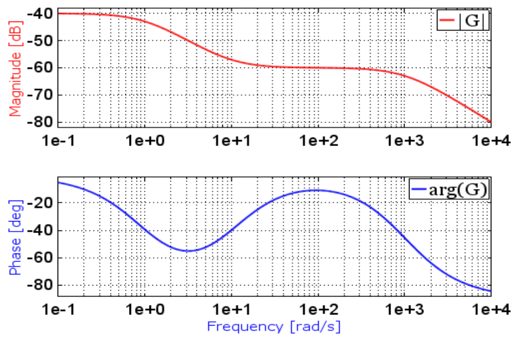
STEP RESPONSE TESTING

1. Apply step input to system
2. Record process variable response
3. Calculate process parameters
4. Use parameters for controller tuning



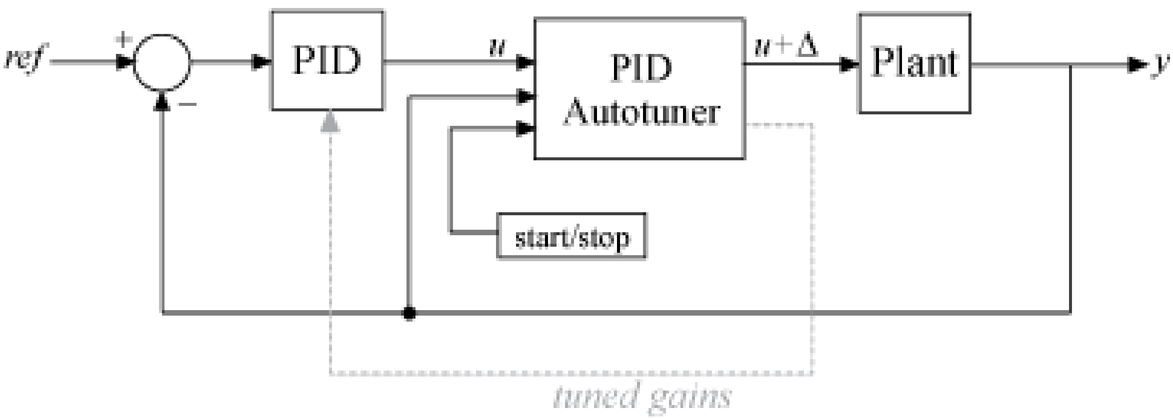
FREQUENCY RESPONSE TESTING

1. Apply sinusoidal input sweep
2. Measure amplitude ratio and phase shift
3. Create Bode plot
4. Design controller for desired margins



AUTO-TUNING ALGORITHMS

- Relay feedback method: Automated critical gain finding
- Pattern recognition: Identify system response patterns
- Adaptive tuning: Continuous parameter adjustment
- Model reference: Compare with ideal response



8. REAL-WORLD APPLICATIONS

8.1 MOTOR CONTROL SYSTEMS

Linear Actuator Position Control

SYSTEM COMPONENTS

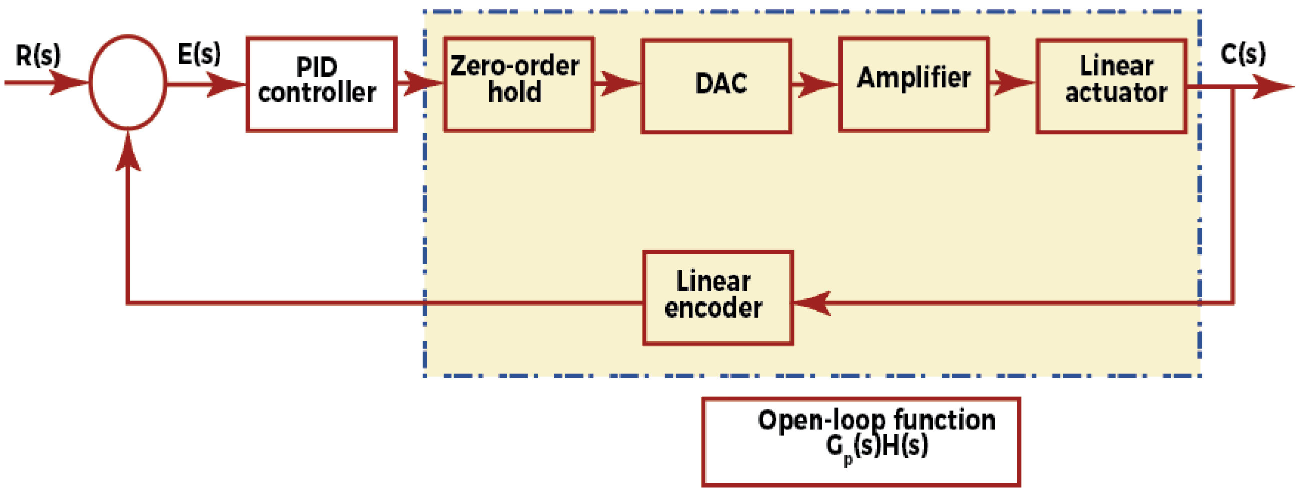
- Plant: Linear Actuator with encoder feedback
- Sensor: Optical encoder (1000 PPR typical)
- Controller Implemented PID in MCU

TYPICAL SPECIFICATIONS

PARAMETER	SPECIFICATION	TYPICAL VALUES
Position accuracy	±0.1°	Encoder resolution limited
Settling time	<100ms	For 90° step input
Following error	<2°	At maximum velocity
Velocity ripple	<5%	Of commanded velocity

CHALLENGES

- Commutation timing: Precise rotor position required
- Current control: Inner current loop for torque control
- Back-EMF compensation: Velocity-dependent voltage drop
- Cogging torque: Periodic disturbances from magnets



8.2 THERMAL CONTROL APPLICATIONS

Temperature Control System Design: Heater Temperature Control

SYSTEM CHARACTERISTICS

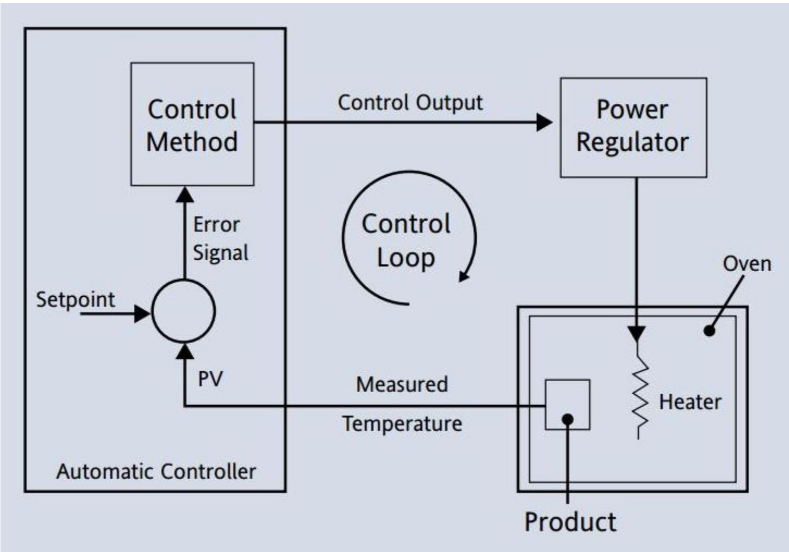
- Plant: Thermal mass with heater
- Sensor: Precision thermistor (0.1°C accuracy)
- Actuator: Linear Peltier driver (±5A)
- Control range: -10°C to +80°C

DESIGN CONSIDERATIONS

ASPECT	CHALLENGE	SOLUTION
Thermal lag	10-100S time constants	Long integration times
Heating/cooling asymmetry	Different time constants	Gain scheduling
Ambient variations	External disturbances	Feed-forward compensation
Power limitations	Peltier current limits	Anti-windup protection

TUNING PARAMETERS

- $\boldsymbol{Kp}: 5-20\ (A/°C)\ -\ \mathit{Based\ on\ thermal\ resistance}$
- $\boldsymbol{Ki}: 0.1-1\ (A/°C-s)\ -\ \mathit{Long\ time\ constants}$
- $\boldsymbol{Kd}: 0.05-0.5\ (A-s/°C)\ -\ \mathit{Filtered\ heavily\ for\ noise}$



9. COMMON PID CIRCUITS

9.1 DISCRETE COMPONENT PID CIRCUITS

OP-AMP BASED PID CONTROLLER

Component Values for Typical Application:

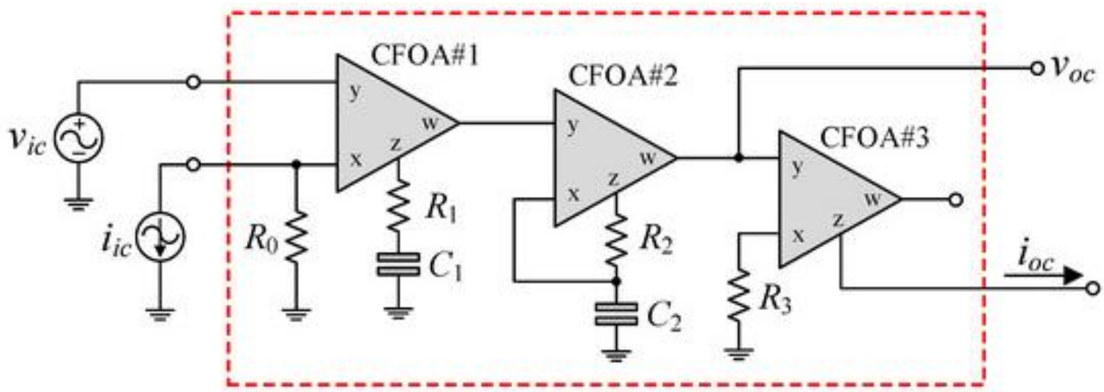
- R0 = 10kΩ (proportional gain setting)
- R1 = 100kΩ (integral time constant)
- C1 = 0.1μF (integral capacitor)
- R2 = 10kΩ (derivative gain)
- C2 = 10nF (derivative filter)
- R3 = 10KΩ (Proportional Gain)

TRANSFER FUNCTION

$$\frac{v_{oc}(s)}{v_{ic}(s)} = \frac{R_3}{R_0} + \frac{R_1}{R_0 C_1} \cdot \frac{1}{s} + R_2 C_2 \cdot \frac{R_3}{R_0} \cdot s$$

DESIGN GUIDELINES

- Op-amp selection: Low offset, high slew rate
- Resistor tolerance: 1% for consistent performance
- Capacitor type: Low leakage for integral term
- Supply voltage: ±15V typical for wide output swing



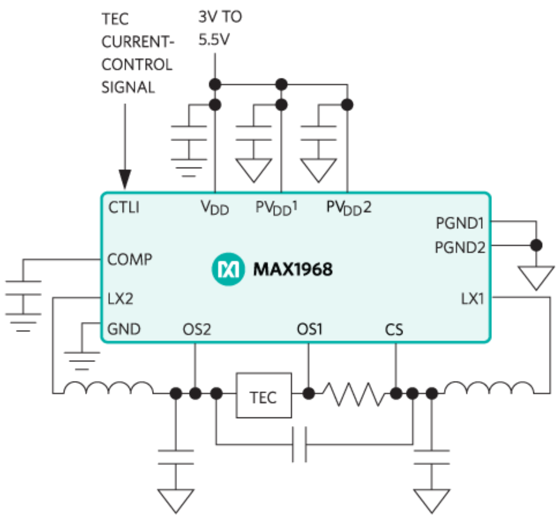
9.2 INTEGRATED CONTROLLER SOLUTIONS

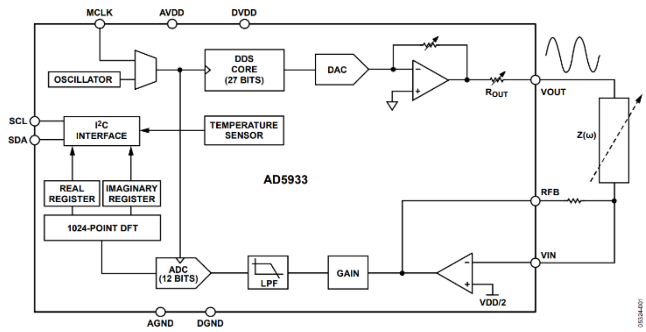
DEDICATED PID CONTROLLER ICS

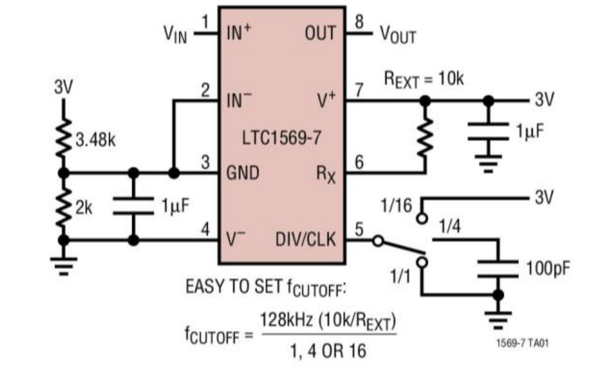
PART NUMBER	FEATURES	RESOLUTION	INTERFACE
MAX1968	3-term PID, 12-bit	0.025%	SPI
LTC1569	Analog PID filter	Continuous	Analog
AD5933	Impedance analyzer PID	12-bit	I^2C

MICROCONTROLLER-BASED SOLUTIONS:

- STM32F4: 32-bit ARM, floating-point unit
- TMS320F28x: Fixed-point DSP controllers







9.3 SYSTEM INTEGRATION CONSIDERATIONS

POWER SUPPLY DESIGN

- Analog circuits: ±15V or ±12V dual supplies
- Digital circuits: +3.3V or +5V single supply
- Isolation: Required for industrial applications
- Noise filtering: LC filters for switching supplies

ELECTROMAGNETIC COMPATIBILITY

- Cable shielding: Twisted pair for differential signals
- Grounding: Single-point ground for analog circuits
- PCB layout: Separate analog and digital ground planes
- Filtering: Ferrite beads and bypass capacitors

SAFETY AND RELIABILITY

- Watchdog circuits: Reset on software failures
- Redundancy: Backup systems for critical applications
- Fail-safe design: Known safe state on power loss
- Environmental protection: Temperature, vibration, moisture

TESTING AND VALIDATION

- Loop testing: Step response verification
- Stability margins: Gain and phase margin measurement
- Disturbance rejection: Load step testing
- Long-term stability: Extended operation testing