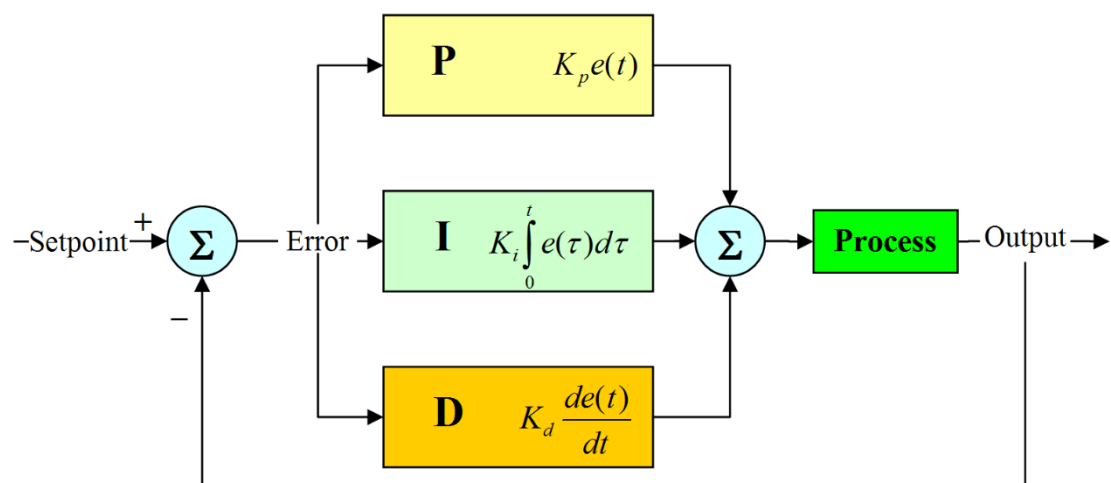
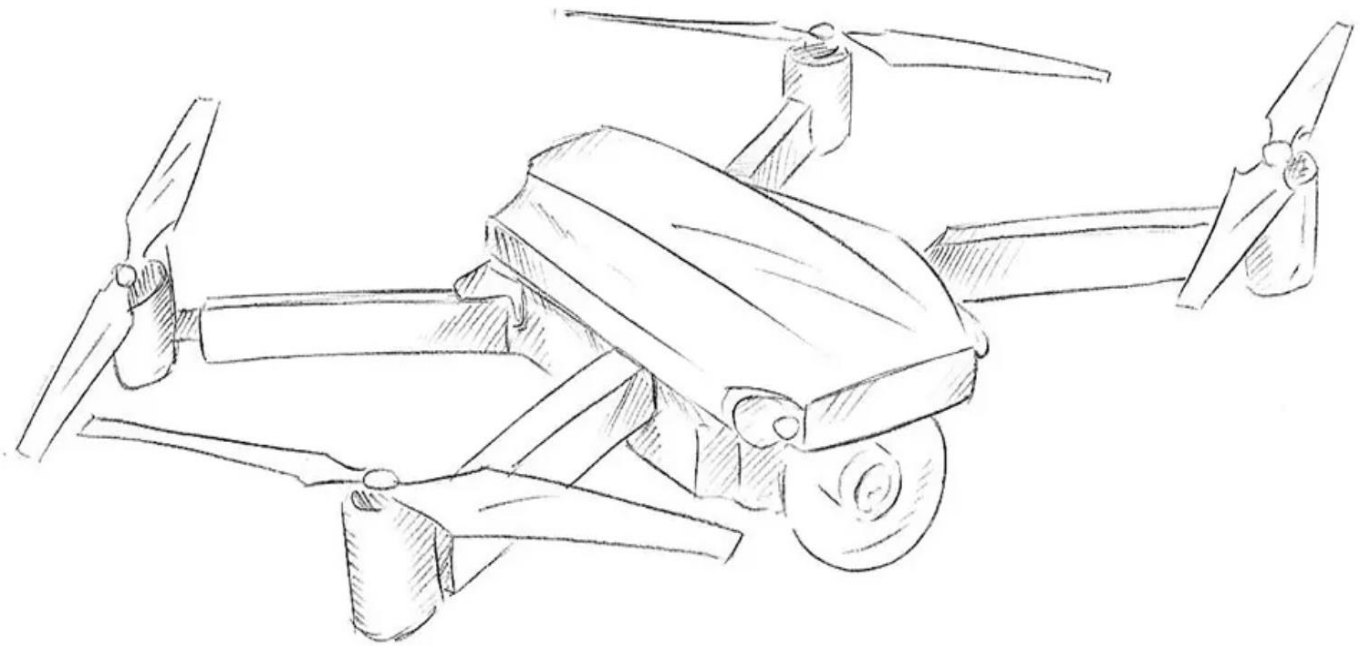


PID CONTROL



By Shimi Cohen

1. PID FUNDAMENTALS

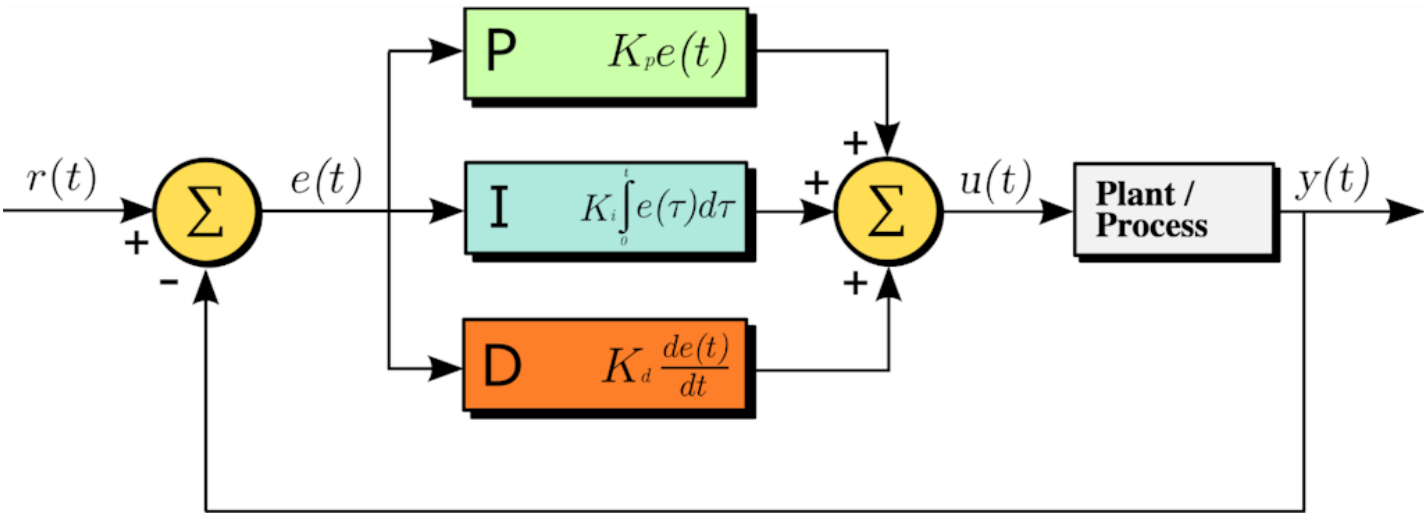
PID FOUNDATION

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 | $Kd \cdot de(t)/dt$ | $Kd \cdot s$ | 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 K_p lower stability but faster response
- Response time: Instantaneous
- Steady accuracy: Limited by proportional band
- Typical K_p 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.)

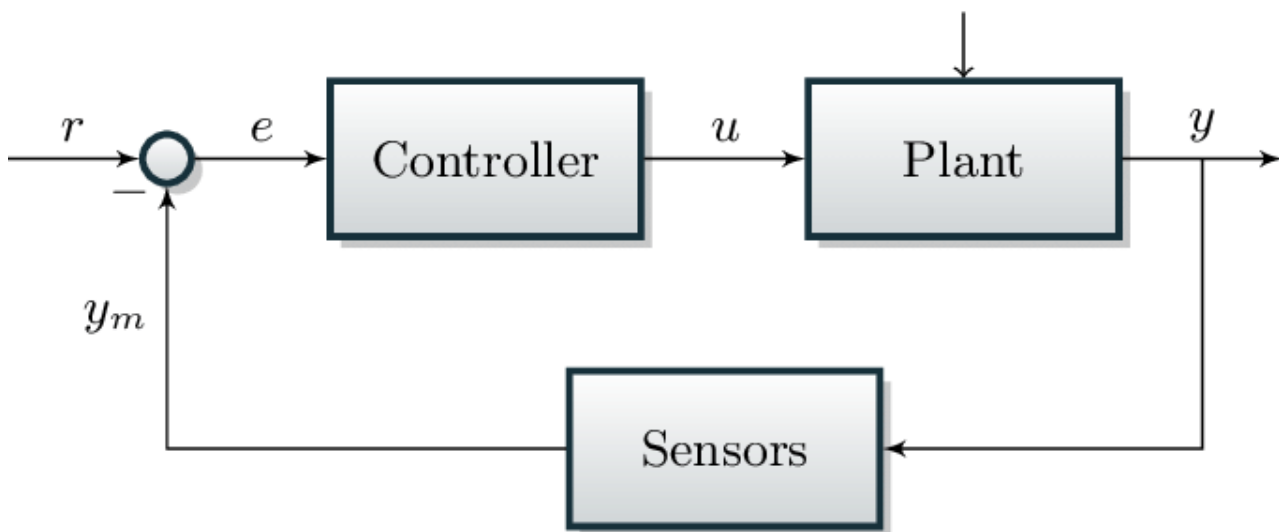
2.1 TIME CONSTANTS AND DELAYS

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, $\pm 10V$ amplifier limits
- Rate constraints: Maximum slew rate limitations
- Physical limits: Temperature, pressure, position boundaries

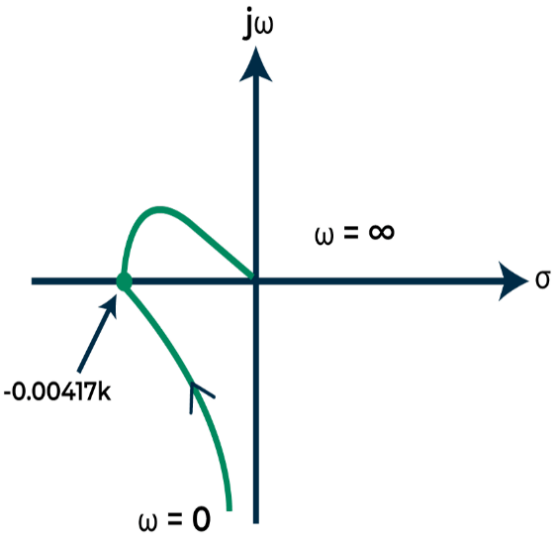
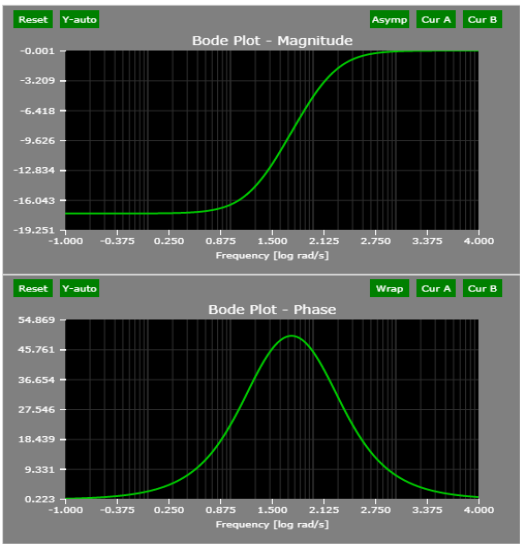
2.3 SYSTEM IDENTIFICATION TECHNIQUES

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

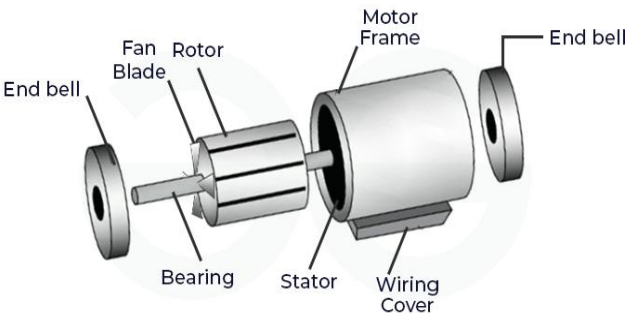
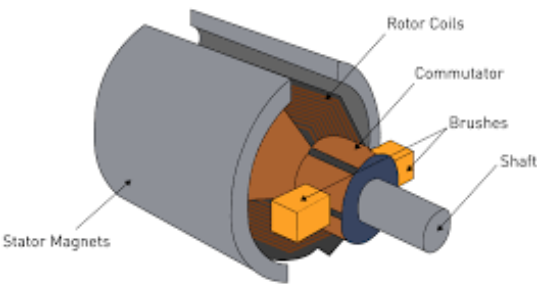


4. FORWARD ARCHITECTURE

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 | $\pm 10V$ 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

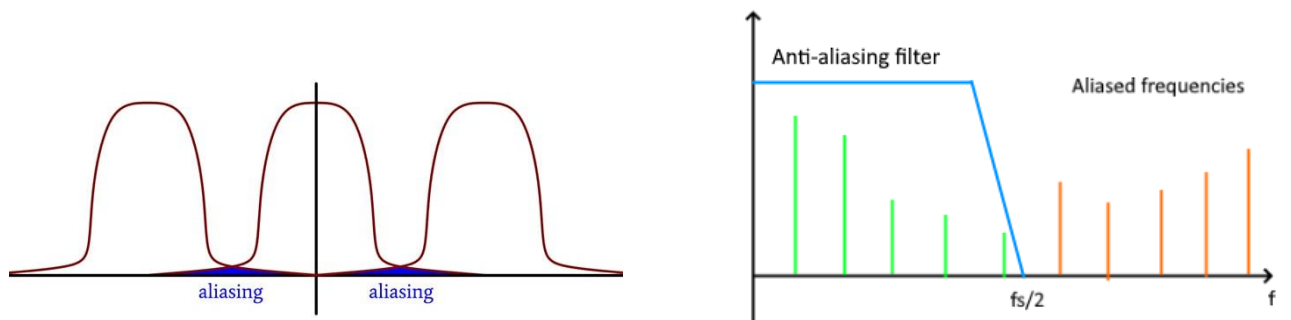
5. SIGNAL PROCESSING

5.1 ANTI-ALIASING AND NOISE REJECTION

ANTI-ALIASING FILTER DESIGN

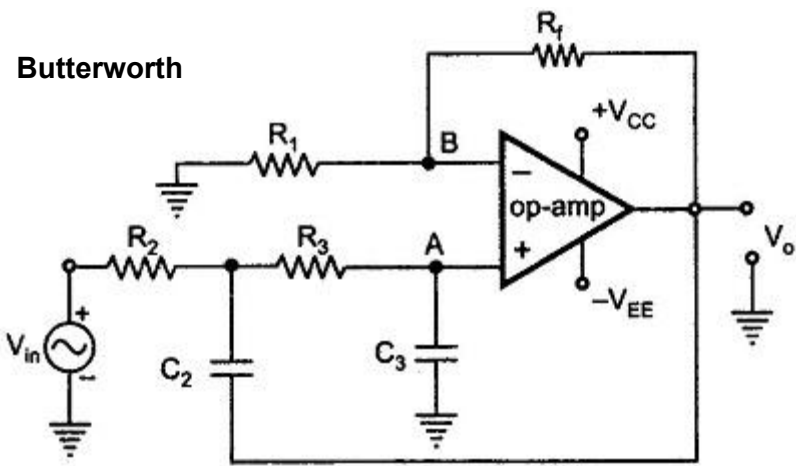
Sampling Rate Selection:

- Nyquist criterion: $f_s > 2 \times f_{max}$
- Practical rule: $f_s = 10 \times \text{control bandwidth}$
- 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 |



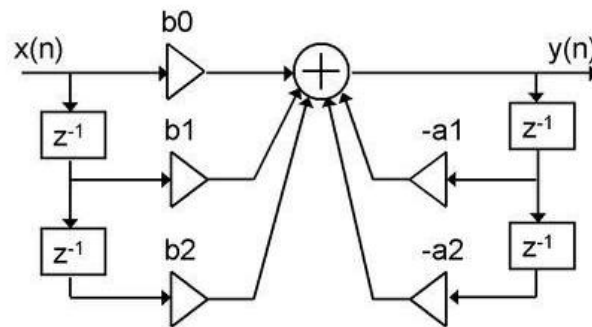
5.2 BIQUAD FILTER STRUCTURES

DIGITAL BI-QUAD IMPLEMENTATION

$$H(z) = (b_0 + b_1 \times z^{-1} + b_2 \times z^{-2}) / (1 + a_1 \times z^{-1} + a_2 \times z^{-2})$$

Coefficient Calculation Methods:

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



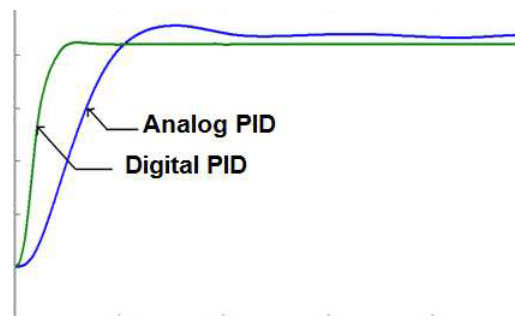
5.3 DIGITAL VS ANALOG FILTERING

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

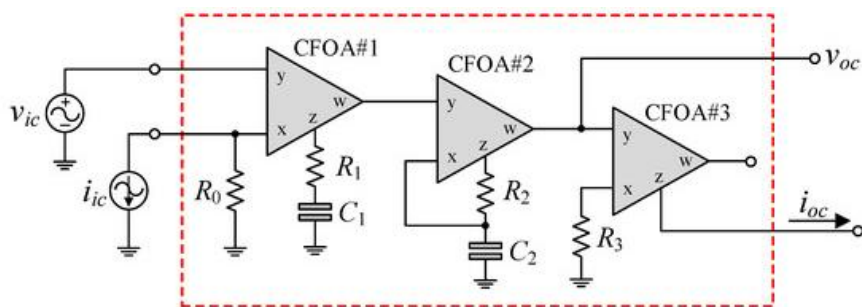


6. PID IMPLEMENTATION

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

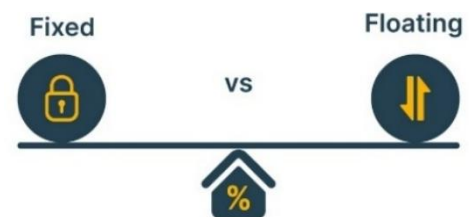
FIXED-POINT VS FLOATING-POINT

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

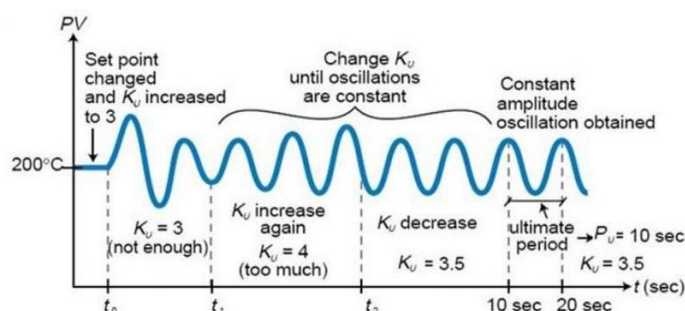
7.1 PRACTICAL TUNING METHODS

ZIEGLER-NICHOLS METHOD

Critical Gain Determination

- Set $K_i = 0$, $K_d = 0$
- Increase K_p until sustained oscillation occurs
- Record critical gain (K_c) and oscillation period (T_c)

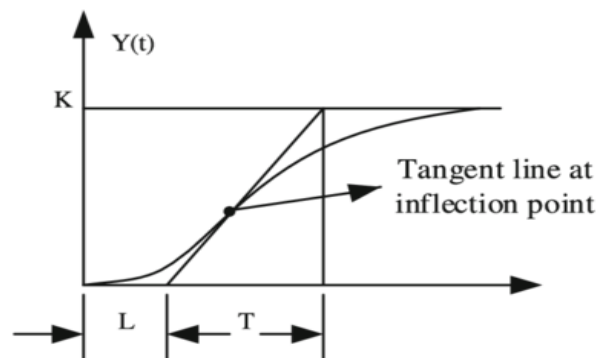
| TYPE | KP | KI | KD |
|---------------|-------------------|------------------------|----------------------|
| P-only | $0.5 \times K_c$ | 0 | 0 |
| PI | $0.45 \times K_c$ | $1.2 \times K_p / T_c$ | 0 |
| PID | $0.6 \times K_c$ | $2 \times K_p / T_c$ | $K_p \times T_c / 8$ |



COHEN-COON METHOD

Based on open-loop step response characteristics:

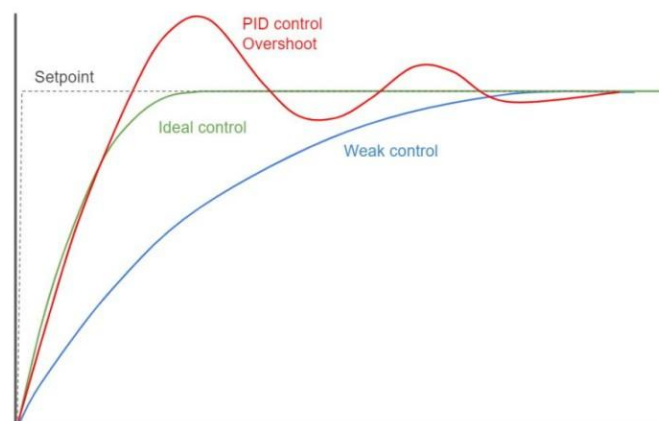
- Process gain (K): Steady-state output change / input change
- Time constant (τ): Time to reach 63% of final value
- Dead time (θ): Time before response begins



7.2 COMMON FAILURE MODES AND SOLUTIONS

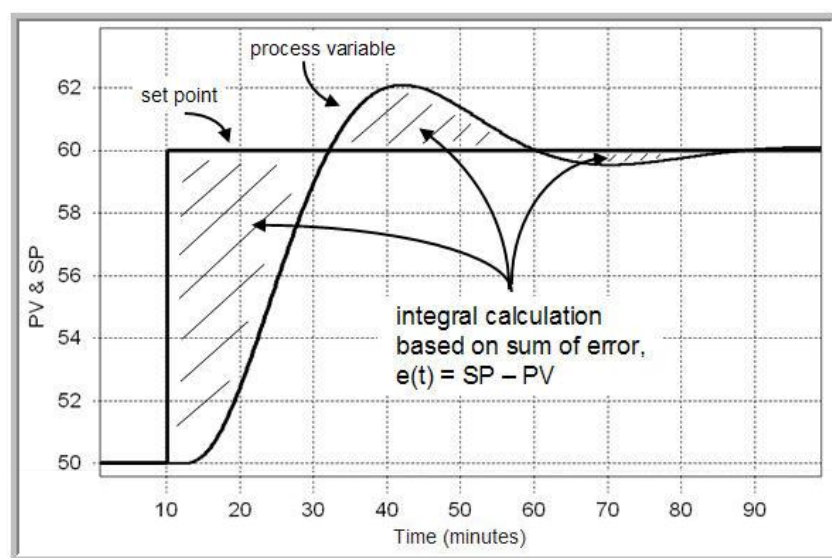
OSCILLATION PROBLEMS

| 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

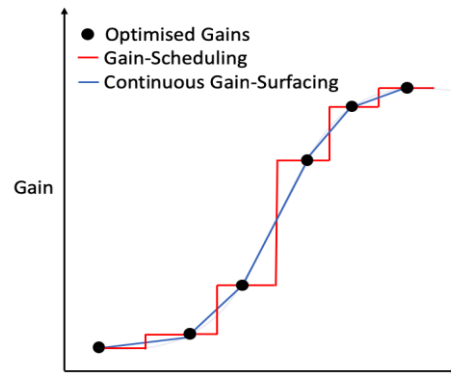
- Conditional integration: Stop integration when output saturated
- Back-calculation: Reduce integral term when output limited
- Clamping: Limit integral term to prevent excessive accumulation



7.3 ADVANCED TUNING TECHNIQUES

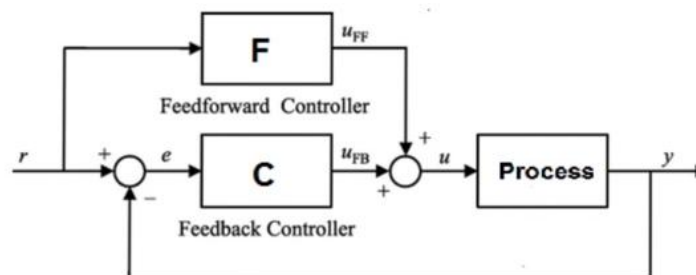
GAIN SCHEDULING

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



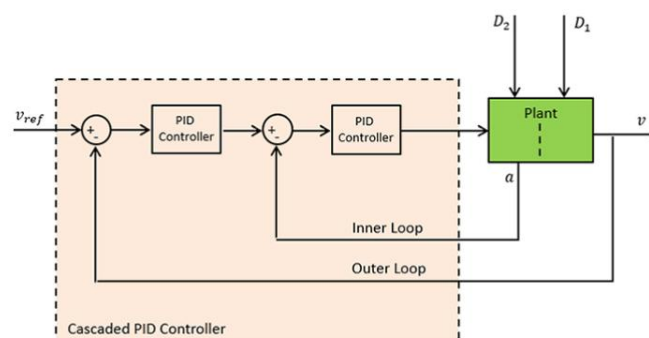
FEED-FORWARD CONTROL

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



CASCADE CONTROL

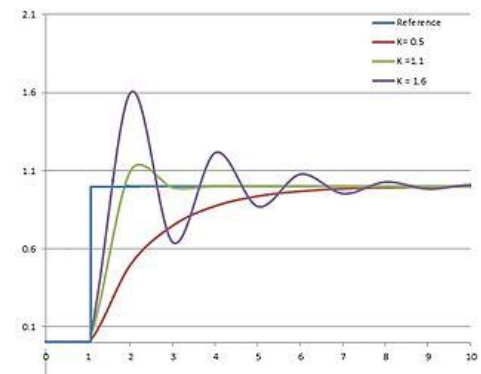
- Inner loop: Fast variable (current, pressure)
- Outer loop: Slow variable (position, temperature)
- Improved disturbance rejection and stability



7.4 SYSTEM IDENTIFICATION FOR BETTER TUNING

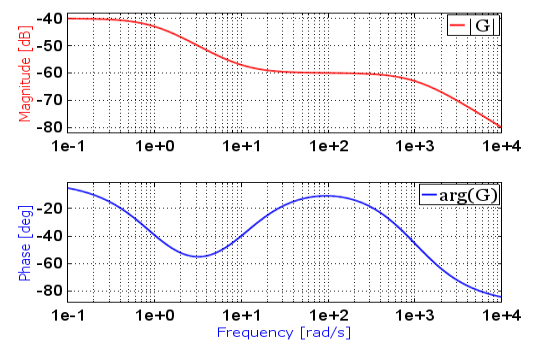
STEP RESPONSE TESTING

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



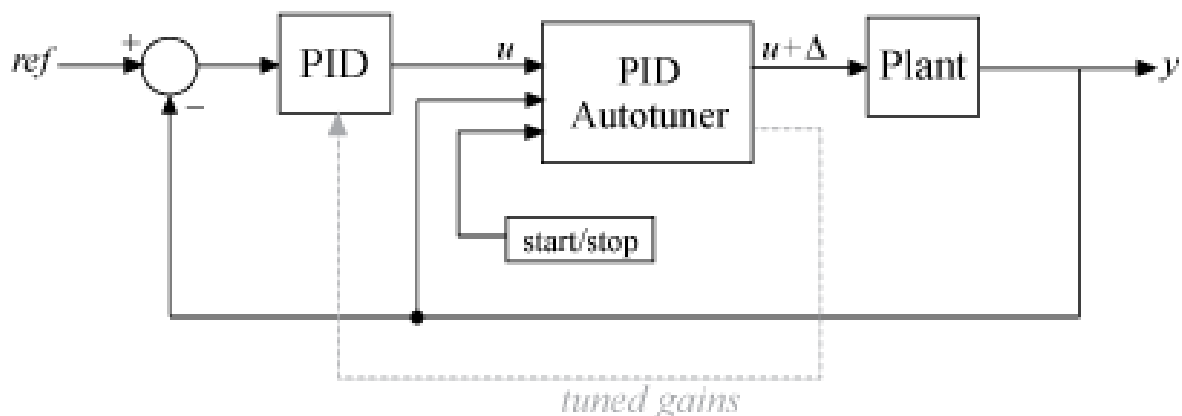
FREQUENCY RESPONSE TESTING

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

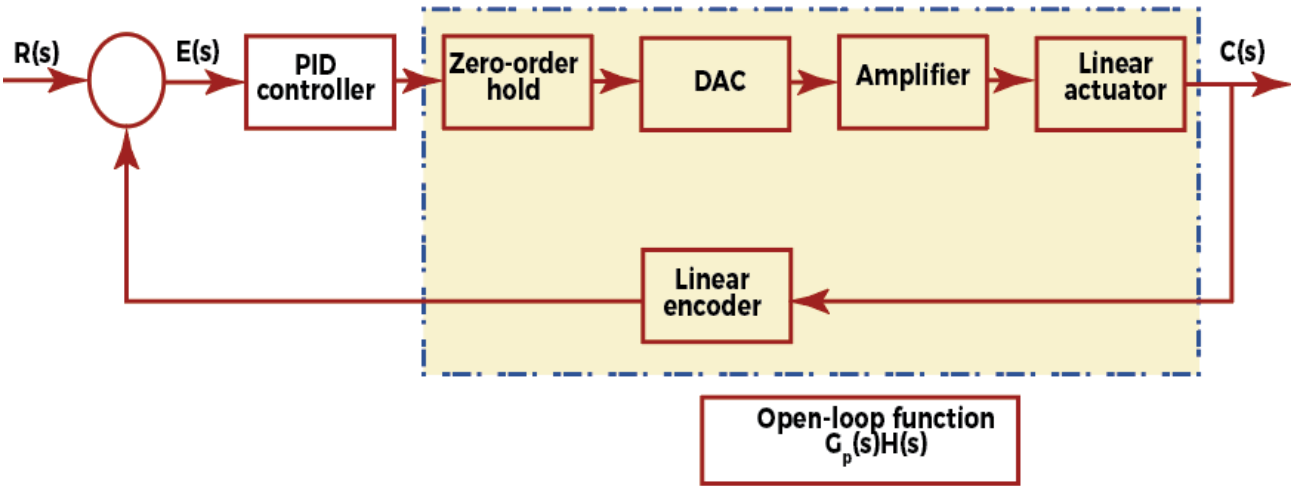
- Plant: Linear Actuator with encoder feedback
- Sensor: Optical encoder (1000 PPR typical)
- Controller Implemented PID in MCU

TYPICAL SPECIFICATIONS

| PARAMETER | SPECIFICATION | TYPICAL VALUES |
|-------------------|------------------|----------------------------|
| Position accuracy | $\pm 0.1^\circ$ | Encoder resolution limited |
| Settling time | $< 100\text{ms}$ | For 90° step input |
| Following error | $< 2^\circ$ | 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

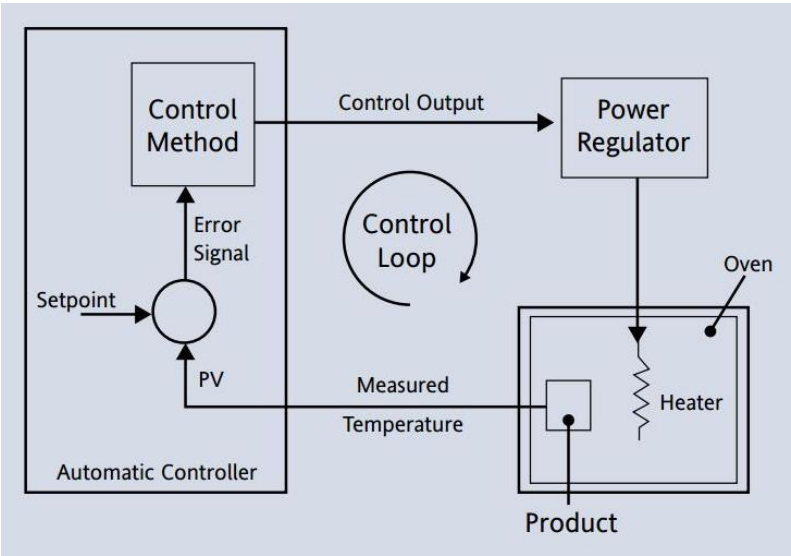
- Plant: Thermal mass with heater
- Sensor: Precision thermistor (0.1°C accuracy)
- Actuator: Linear Peltier driver (±5A)
- Control range: -10°C to +80°C

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

- *Kp*: 5 – 20 (A/°C) – Based on thermal resistance
- *Ki*: 0.1 – 1 (A/°C – s) – Long time constants
- *Kd*: 0.05 – 0.5 (A – s/°C) – Filtered heavily for noise



9. COMMON PID CIRCUITS

9.1 DISCRETE COMPONENT PID CIRCUITS

OP-AMP BASED PID CONTROLLER

Component Values for Typical Application:

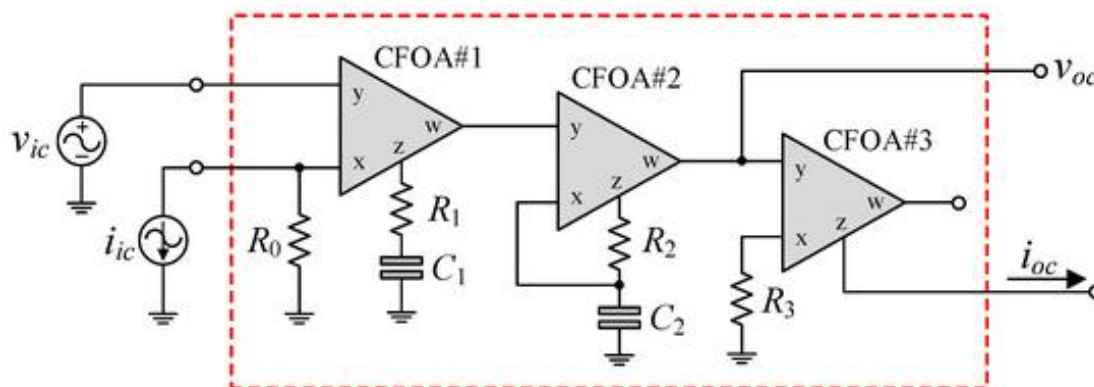
- $R_0 = 10\text{k}\Omega$ (proportional gain setting)
- $R_1 = 100\text{k}\Omega$ (integral time constant)
- $C_1 = 0.1\mu\text{F}$ (integral capacitor)
- $R_2 = 10\text{k}\Omega$ (derivative gain)
- $C_2 = 10\text{nF}$ (derivative filter)
- $R_3 = 10\text{k}\Omega$ (Proportional Gain)

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: $\pm 15\text{V}$ typical for wide output swing



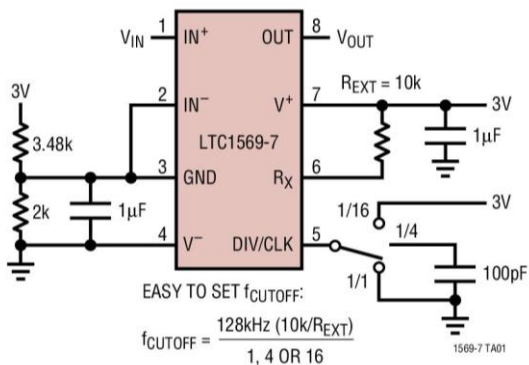
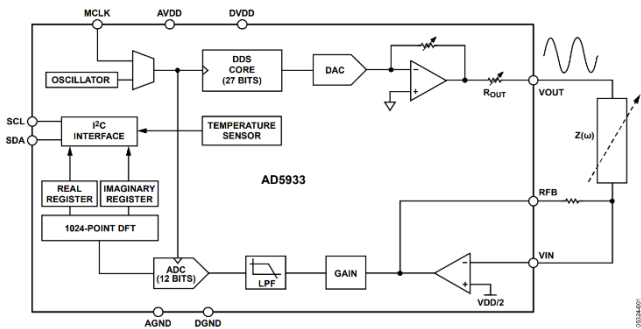
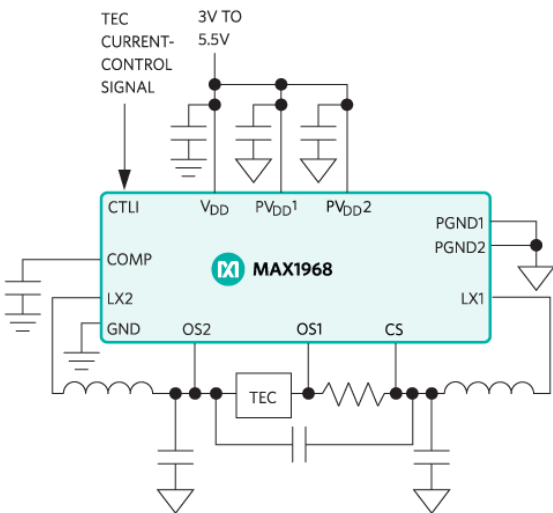
9.2 INTEGRATED CONTROLLER SOLUTIONS

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 ² C |

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: $\pm 15\text{V}$ or $\pm 12\text{V}$ dual supplies
- Digital circuits: $+3.3\text{V}$ or $+5\text{V}$ 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