VentCon2 Pressure Control System

Embedded Software Architecture and Class Documentation

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Contents

1 Executive Summary

The VentCon2 system is a sophisticated embedded pressure control system designed for ventilator applications. Built on the ESP32 Arduino Nano platform, it implements a real-time PID control loop with web-based monitoring and configuration capabilities. The system features automatic parameter tuning, multi-sensor support, and comprehensive safety mechanisms.

1.1 Key Features

- Real-time PID pressure control with configurable parameters
- Memory-efficient web interface with streamed HTML from PROGMEM
- Chunked file serving for large JavaScript libraries (Chart.js)
- Automatic PID tuning using relay-based oscillation methods
- Multi-core task management using FreeRTOS
- Dual ADC support (ADS1015 external, ESP32 internal fallback)
- Persistent configuration storage using LittleFS (3.375 MB partition)
- Serial command interface for advanced control
- WiFi Access Point with client management and channel selection

2 System Architecture Overview

2.1 Introduction

The VentCon2 Pressure Control System is an embedded control solution designed to precisely regulate pressure in medical ventilator applications. At its core, the system maintains a user-defined target pressure by controlling an electronically-operated solenoid valve based on continuous feedback from a high-precision pressure sensor. This section provides an overview of the system's primary components and their interactions.

2.2 System Purpose and Application

The VentCon2 system operates within a pressurized gas delivery circuit, regulating pressure to precise specifications required by medical ventilators. The system is responsible for:

- Maintaining stable pressure at a user-configured setpoint (0-10 bar range)
- Responding rapidly to pressure disturbances and demand changes
- Preventing overshoot and oscillation through advanced control algorithms
- Providing real-time monitoring and diagnostics via web interface and serial console
- Ensuring safe operation with hardware and software redundancy

The system processes pressure feedback hundreds of times per second, adjusting valve opening in real-time to maintain the target pressure with high accuracy and responsiveness.

2.3 Core Hardware Components

2.3.1 Solenoid Valve

The solenoid valve is the primary actuator in the VentCon2 system, responsible for controlling the flow of pressurized gas. Key characteristics:

- **Type:** Electronically-controlled solenoid valve with proportional control capability
- **Control Signal:** PWM (Pulse Width Modulation) at configurable frequency (100-10000 Hz)
- **Operating Principle:** Varying the PWM duty cycle (0-100%) proportionally adjusts the valve's opening position
- **Response Time:** Fast response enables real-time pressure control in the 100 Hz control loop
- **Deadband:** Physical deadband in the valve mechanism creates hysteresis (described in Control System Enhancements section)

The solenoid valve converts electrical PWM signals from the microcontroller into precise mechanical valve positioning. The proportional relationship between PWM duty cycle and valve opening allows the system to achieve smooth, linear pressure control across the full operating range. The valve's physical limitations (deadband, response lag) are compensated by control algorithms described later in the ControlSystem class documentation.

2.3.2 Pressure Sensor

The pressure sensor continuously monitors the system pressure, providing real-time feedback to the control algorithm. Specifications:

- **Sensor Type:** Analog pressure transducer with 0.5-4.5V output signal
- **Pressure Range:** 0-10 bar (0-145 PSI)
- **Measurement Accuracy:** $\pm 2\%$ over the operating range
- **Response Speed:** Suitable for real-time feedback in control loop (< 10 ms delay)
- **Signal Conditioning:** Converted to digital values via 12-bit analog-to-digital converter
- **Filtering:** Software low-pass filter reduces sensor noise (configurable, 0.0-1.0 strength)

The sensor output is continuously digitized and read by the microcontroller's ADC (Analog-to-Digital Converter). The digital pressure values are then passed to the PID control algorithm, which calculates the error between the measured pressure and the target setpoint. This feedback loop operates at 100 Hz (configurable via CONTROL FREQ command), allowing the system to respond rapidly to pressure changes.

2.3.3 Microcontroller and Processing Unit

The brain of the VentCon2 system is the ESP32-S3 Arduino Nano microcontroller. Key capabilities:

- **Processor:** Dual-core Xtensa processor running at 240 MHz
- **Memory:** 320 KB RAM for real-time operations, 16 MB flash storage
- **Analog Input:** 12-bit internal ADC with multiple input channels for sensor reading
- **Digital Output:** PWM-capable GPIO pins for solenoid valve control
- **Communication:** WiFi (802.11 b/g/n) for web interface and diagnostics
- **Serial Port:** UART at 115200 baud for command interface and debugging
- **Real-Time Operating System:** FreeRTOS for multi-tasking and task scheduling

The microcontroller runs the complete VentCon2 software stack including:

- Real-time PID control loop (100+ Hz, core 1)
- Sensor reading and signal processing
- WiFi access point and web server (core 0)
- Serial command processor for advanced control
- Auto-tuning algorithm for parameter optimization
- Persistent settings storage in LittleFS flash filesystem

The dual-core architecture allows separation of critical real-time control (core 1) from network operations (core 0), ensuring that web interface activity does not interfere with pressure control stability.

2.4 System Integration and Signal Flow

2.4.1 Closed-Loop Control Architecture

The VentCon2 system operates as a closed-loop feedback control system:

1. **Measurement:** Pressure sensor continuously measures system pressure
2. **Calculation:** PID algorithm computes error (setpoint - measured pressure)
3. **Control:** Algorithm determines required valve opening (PWM duty cycle)
4. **Actuation:** Solenoid valve adjusts position based on PWM signal
5. **Response:** Pressure change results from valve adjustment
6. **Feedback:** New pressure measurement begins next control cycle

This cycle repeats continuously at 100 Hz (or user-configured frequency), creating a real-time feedback loop that maintains pressure at the setpoint.

2.4.2 System Overview Illustration

Figure 1 illustrates the closed-loop signal flow between the sensor, controller, and solenoid valve.

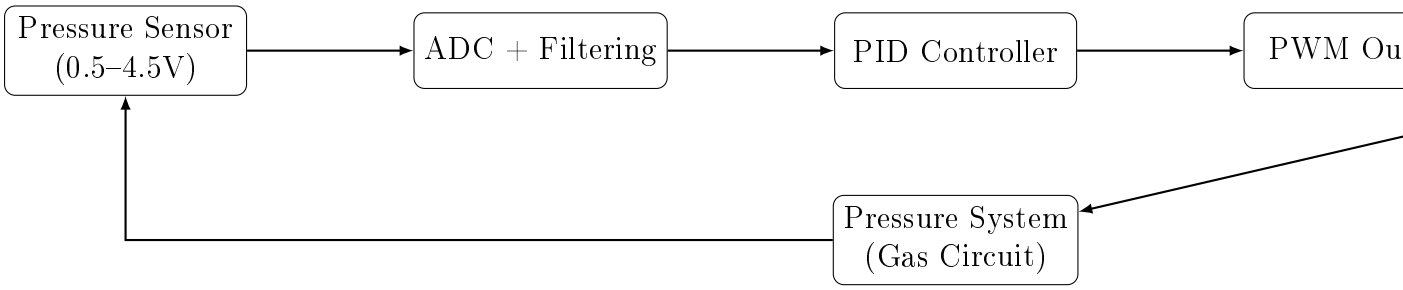

Figure 1: VentCon2 closed-loop control overview

2.4.3 Signal Conditioning and Processing Chain

From sensor to control output, the signal undergoes several processing stages:

$$\text{Voltage} \rightarrow \text{ADC} \rightarrow \text{Digital} \rightarrow \text{Filter} \rightarrow \text{PID} \rightarrow \text{PWM} \tag{1}$$

- **Analog Voltage (0.5-4.5V):** Output from pressure transducer
- **ADC Conversion:** 12-bit analog-to-digital conversion (0-4095 counts)
- **Pressure Conversion:** Digital counts converted to pressure units (bar)
- **Low-Pass Filter:** Software filter reduces high-frequency sensor noise
- **PID Calculation:** Controller computes error and optimal output
- **PWM Generation:** Digital output converted to PWM signal (0-100% duty cycle)
- **Solenoid Actuation:** PWM controls valve opening position

Each processing stage is tunable via serial commands or the web interface, allowing the system to be optimized for different valve characteristics and installation conditions.

2.4.4 External Interfaces

The VentCon2 system provides multiple interfaces for monitoring and control:

- **Web Interface:** Browser-based real-time monitoring and parameter adjustment (WiFi)
- **Serial Console:** Command-line interface for advanced control and diagnostics (USB/UART at 115200 baud)
- **Analog Output:** Optional analog output for pressure telemetry to external equipment
- **GPIO Pins:** General-purpose I/O for integration with external systems

2.5 Hardware Platform

- **Microcontroller:** ESP32-S3 Arduino Nano (Dual-core, 240MHz, 320KB RAM)
- **Flash:** 16MB with custom partition table (6.25MB app, 3.375MB LittleFS)
- **ADC:** ADS1015 12-bit external ADC with ESP32 internal ADC fallback
- **Pressure Sensor:** 0.5-4.5V analog output, 0-10 bar range
- **Valve Control:** PWM-controlled solenoid valve
- **Connectivity:** WiFi Access Point mode (WPA2-PSK)
- **Storage:** LittleFS for persistent configuration and web assets

2.6 Software Architecture

The VentCon2 software architecture employs modern object-oriented design patterns to create a robust, maintainable, and scalable embedded system. Built around the principle of separation of concerns, the architecture divides system functionality into eight specialized classes, each responsible for distinct aspects of the pressure control system. The design leverages dependency injection to promote loose coupling between components, enabling comprehensive unit testing and facilitating future system enhancements. This modular approach ensures that critical real-time control operations remain isolated from network communications and user interface management, optimizing both performance and reliability.

2.6.1 System Overview Diagram

Figure 2 shows the high-level architecture with class relationships and data flow between components.

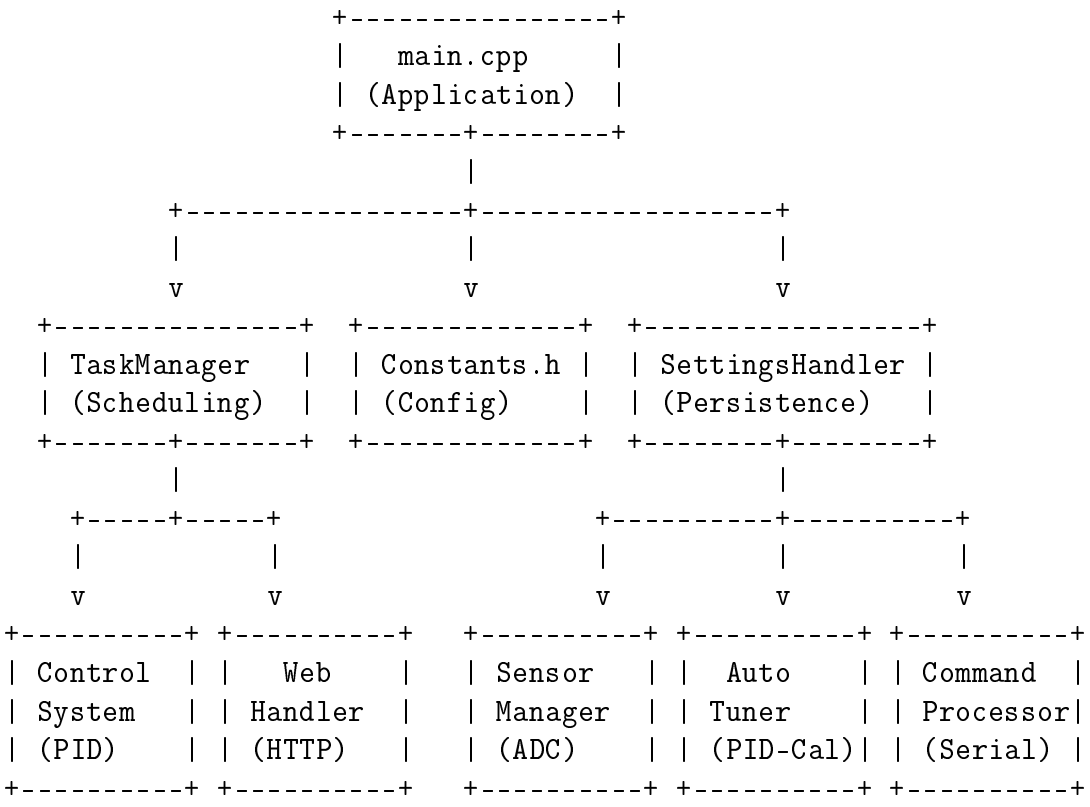

Figure 2: VentCon2 System Architecture Overview

2.6.2 Design Patterns Used

- **Dependency Injection**: main.cpp creates and injects all dependencies
- **Observer Pattern**: Real-time data updates from control to web interface
- **Strategy Pattern**: Pluggable auto-tuning algorithms (Ziegler-Nichols, etc.)
- **Singleton Pattern**: Constants namespaces provide global configuration
- **Factory Pattern**: TaskManager handles FreeRTOS task creation

2.6.3 Class Summary Tables

The following tables document each class with its attributes and methods.

Table 1: SettingsHandler Class

Type	Member	Description
Attributes		
double	Kp, Ki, Kd	PID controller gains
double	setpoint	Target pressure (bar)
int	pwm_freq, pwm_res	PWM configuration
float	filter_strength	Low-pass filter coefficient
bool	antiWindup, hysteresis	Control enhancements
Methods		
bool	load()	Load settings from LittleFS
bool	save()	Save settings to LittleFS
void	resetToDefaults()	Restore factory defaults
void	printSettings()	Debug output to Serial

Table 2: SensorManager Class

Type	Member	Description
Attributes		
Adafruit_ADS1015	ads	External ADC instance
bool	ads_found	ADC detection flag
int16_t	adc_value	Raw ADC reading
float	voltage, raw_pressure	Converted values
float	filtered_pressure	After low-pass filter
Methods		
bool	initialize()	Setup I2C and ADC
void	readSensor()	Read and convert ADC
float	getPressure()	Get current pressure
float*	getFilteredPtr()	Pointer for PID input

Table 3: WebHandler Class

Type	Member	Description
Attributes		
WebServer	webServer	ESP32 HTTP server (port 80)
DNSServer	webDnsServer	Captive portal DNS
bool	webServerEnabled	Server state flag
int	connectedClients	Active client counter
Methods		
void	handleRoot()	Stream HTML from PROGMEM
void	handleValues()	JSON API for live data
void	handleSet()	Process parameter changes
void	initializeWiFiAP()	Start AP with WIFI_AP mode
void	scanWiFiNetworks()	Return JSON network list

Table 4: ControlSystem Class

Type	Member	Description
Attributes		
PID*	pid	PID controller instance
double*	pressureInput	Pointer to sensor reading
double*	pwmPIDoutput	Pointer to valve output
bool*	manualPWMMode	Manual override flag
Methods		
bool	initialize()	Setup PID with settings
void	processControlLoop()	Execute one PID cycle
void	updatePWMOutput()	Apply PWM to valve
void	emergencyShutdown()	Safe state on error
void	handleDataOutput()	Send data to clients

Table 5: AutoTuner Class

Type	Member	Description
Attributes		
bool	autoTuneRunning	Tuning active flag
float	autoTuneSetpoint	Target for oscillation
int	currentCycle	Oscillation counter
ulong[]	cycleTimes	Period measurements
float[]	cycleAmplitudes	Amplitude measurements
enum	currentTuningRule	Algorithm selection
Methods		
void	start()	Begin relay tuning
void	stop()	Abort and restore PID
void	process()	Execute tuning step
float	getProgress()	0.0–1.0 completion
void	setTuningRule()	Select calculation method

Table 6: CommandProcessor Class

Type	Member	Description
Attributes		
String	commandBuffer	Incoming serial data
Pointers	settings, sensor, etc.	References to all subsystems
Methods		
void	handleSerialInput()	Read and buffer chars
bool	executeCommand()	Parse and dispatch
void	showHelp()	Print command list
void	showStatus()	Print system state
void	handlePIDCmd()	PID parameter commands
void	handlePWMCmd()	Manual PWM commands

Table 7: TaskManager Class

Type	Member	Description
Attributes		
TaskHandle_t	controlTaskHandle	FreeRTOS control task
TaskHandle_t	networkTaskHandle	FreeRTOS network task
bool	taskRunning	Tasks active flag
Methods		
bool	createTasks()	Spawn FreeRTOS tasks
void	startTasks()	Resume suspended tasks
void	stopTasks()	Suspend running tasks
bool	getTaskStatus()	Query task states
void	monitorTasks()	Watchdog and recovery

Table 8: Constants.h Namespaces

Namespace	Constant	Value / Description
NetworkConfig	AP_SSID	"VENTCON_AP"
NetworkConfig	AP_PASSWORD	"ventcon12!" (WPA2-PSK)
HardwareConfig	SOLENOID_PIN	GPIO for valve PWM
HardwareConfig	ANALOG_PRESS_PIN	ADC input pin
SensorConfig	SENSOR_MIN_BAR	0.0 (minimum range)
SensorConfig	SENSOR_MAX_BAR	10.0 (maximum range)
ValveConfig	VALVE_MIN_DUTY	50.0% (minimum effective duty cycle)
ValveConfig	VALVE_MAX_DUTY	90.0% (maximum safe duty cycle)

3 Core Classes Documentation

3.1 SettingsHandler Class

3.1.1 Purpose

The SettingsHandler class encapsulates all system configuration parameters and provides persistent storage capabilities using LittleFS. It serves as the central configuration repository for all system components.

3.1.2 Key Responsibilities

- Manage PID controller parameters (Kp, Ki, Kd, setpoint)
- Store PWM configuration (frequency, resolution)
- Handle sensor filtering parameters
- Provide JSON serialization/deserialization
- Automatic load/save to flash storage
- Parameter validation and constraints

3.1.3 Key Attributes

```
// SliderLimits structure for UI customization
struct SliderLimits {
    float min;                    // Minimum slider value
    float max;                    // Maximum slider value
    float step;                   // Slider step increment
};

class SettingsHandler {
public:
    // PID Parameters
    double Kp;                    // Proportional gain
    double Ki;                    // Integral gain
    double Kd;                    // Derivative gain

    // System Parameters
    float filter_strength;        // Low-pass filter coefficient
    double setpoint;              // Target pressure in bar
    int pwm_freq;                 // PWM frequency in Hz
    int pwm_res;                  // PWM resolution in bits
    int pid_sample_time;          // PID sample time in ms
    int control_freq_hz;          // Control loop frequency

    // Advanced Features
    bool antiWindup;              // Anti-windup enable flag
    bool hysteresis;              // Hysteresis compensation
    float hystAmount;             // Hysteresis amount (percentage)

    // Slider Limits (user-configurable via web UI)
    SliderLimits sp_limits;       // Setpoint slider limits
    SliderLimits kp_limits;       // Kp slider limits
    SliderLimits ki_limits;       // Ki slider limits
    SliderLimits kd_limits;       // Kd slider limits

    // Constructor with default values
    SettingsHandler();

    // Methods
    bool load();                  // Load from LittleFS
    bool save();                  // Save to LittleFS
    void resetToDefaults();       // Reset to default values
    void printSettings();         // Display current settings
    void printStoredSettings();   // Display stored settings
};
```

Listing 1: SettingsHandler Class Key Members - Actual Implementation

3.2 SensorManager Class

3.2.1 Purpose

The SensorManager class handles all sensor-related operations, providing a unified interface for pressure sensing with automatic fallback mechanisms and signal processing.

3.2.2 Key Responsibilities

- ADS1015 external ADC initialization and communication
- ESP32 internal ADC fallback when external ADC fails
- Voltage to pressure conversion calculations
- Low-pass filtering for noise reduction
- Sensor health monitoring and diagnostics

3.2.3 Key Attributes

```
class SensorManager {
private:
    Adafruit_ADS1015 ads;          // External ADC instance
    bool ads_found;                // ADC availability flag
    int16_t adc_value;            // Raw ADC reading
    float voltage;                // Converted voltage
    float raw_pressure;           // Unfiltered pressure
    float filtered_pressure;      // Filtered pressure
    SettingsHandler* settings;          // Configuration reference

public:
    SensorManager(SettingsHandler* settings);
    bool initialize();            // Hardware initialization
    void readSensor();           // Main sensor reading function
    float getPressure();         // Get filtered pressure
    bool isADSFound();          // Check ADC status
    float* getLastFilteredPressurePtr(); // For web interface
};
```

Listing 2: SensorManager Class Structure

3.2.4 Sensor Specifications

Parameter	Value
Voltage Range	0.5V - 4.5V
Pressure Range	0 - 10 bar
ADC Resolution	12-bit (ADS1015)
Sample Rate	Up to 1600 SPS
I2C Address	0x48
Fallback Pin	A0 (ESP32 internal)

Table 9: Sensor Configuration Parameters

3.3 AutoTuner Class

3.3.1 Purpose

The AutoTuner class implements relay-based auto-tuning for PID controller parameters using the Ziegler-Nichols frequency response method and other tuning algorithms.

3.3.2 Tuning Algorithm

The auto-tuner uses relay oscillation to identify the critical frequency and amplitude of the system, then applies tuning rules to calculate optimal PID parameters.

$$K_c = \frac{4M}{\pi A} \tag{2}$$

$$T_c = 2 \cdot T_{osc} \tag{3}$$

Where:

- K_c = Critical gain
- M = Relay amplitude
- A = Process oscillation amplitude
- T_c = Critical period
- T_{osc} = Measured oscillation period

3.3.3 Tuning Rules

Rule	Kp	Ki	Kd
Ziegler-Nichols Classic	$0.6K_c$	$\frac{2K_p}{T_c}$	$\frac{K_pT_c}{8}$
Ziegler-Nichols Aggressive	$0.33K_c$	$\frac{2K_p}{T_c}$	$\frac{K_pT_c}{3}$
Tyreus-Luyben	$0.454K_c$	$\frac{K_p}{2.2T_c}$	$\frac{K_pT_c}{6.3}$
Pessen Integral	$0.7K_c$	$\frac{2.5K_p}{T_c}$	$\frac{K_pT_c}{6.25}$

Table 10: Auto-Tuning Rules Implemented

3.3.4 Class Structure

```
class AutoTuner {
private:
    // Auto-tuning state variables
    bool autoTuneRunning;
    unsigned long autoTuneStartTime;
    unsigned long lastTransitionTime;
    float autoTuneOutputValue;
    float autoTuneSetpoint;
    bool autoTuneState;
    int currentCycle;

    // Cycle data collection
    static constexpr int MAX_CYCLES = 20;
    unsigned long cycleTimes[MAX_CYCLES];
    float cycleAmplitudes[MAX_CYCLES];

    // Amplitude tracking
    float maxPressure;
    float minPressure;
```

```
    bool firstCycleComplete;

    // Configuration parameters
    float testSetpoint;
    float minPwmValue;
    float maxPwmValue;
    unsigned long minCycleTime;
    TuningRule currentTuningRule;
    float tuningAggressiveness;

    // System references
    SettingsHandler* settings;
    PID* pid;
    double* pressureInput;
    int* pwmMaxValue;

public:
    AutoTuner(SettingsHandler* settings, PID* pid, double* pressureInput
        , int* pwmMaxValue);
    void start();
    void stop(bool calculateParameters = false);
    void process();
    bool isRunning() const;
    float getOutputValue() const;
    void acceptParameters();
    void rejectParameters();
    void setTestSetpoint(float setpoint);
    void setTuningRule(TuningRule rule);
    void setAggressiveness(float aggr);
    void setMinMaxPWM(float minPwm, float maxPwm);
    void setMinCycleTime(unsigned long cycleTime);
    float getTestSetpoint() const;
    TuningRule getTuningRule() const;
    float getAggressiveness() const;
    float getMinPWM() const;
    float getMaxPWM() const;
    float getEffectiveAmplitude() const;
    unsigned long getMinCycleTime() const;
    void printTuningRules() const;
    void printConfiguration() const;
};
```

Listing 3: AutoTuner Class Key Members - Actual Implementation

3.4 ControlSystem Class

3.4.1 Purpose

The ControlSystem class implements the main control loop, integrating PID control, sensor reading, valve control, and safety mechanisms in a real-time task.

3.4.2 Control Loop Structure

```
void ControlSystem::processControlLoop() {
    TickType_t lastWakeTime = xTaskGetTickCount();

```

```
    // Use configurable frequency
    TickType_t frequency = pdMS_TO_TICKS(1000 / settings->
        control_freq_hz);

    static unsigned long lastCycleEnd = 0;

    while(true) {
        // Update frequency if settings changed
        frequency = pdMS_TO_TICKS(1000 / settings->control_freq_hz);
        unsigned long taskStartTime = micros();

        // ====== Sensor Reading using SensorManager ======
        sensorManager->readSensor();

        // Save last pressure before updating, used for hysteresis
            compensation
        lastPressure = *pressureInput;

        // Update Input value for PID before computation
        *pressureInput = sensorManager->getPressure();

        // ====== Analog Pressure Signal Output =====
        handleAnalogPressureOutput();

        // Process auto-tuning if active
        if (autoTuner && autoTuner->isRunning()) {
            autoTuner->process();
        }
        // PID calculation and PWM output (only if not in auto-tune mode
            )
        else if (!*manualPWMMode) {
            // Store previous output for anti-windup check
            double previousOutput = *pwmPIDoutput;

            // Constrain output to valid range
            *pwmPIDoutput = constrain(*pwmPIDoutput, 0, *pwmFullScaleRaw
                );

            // Compute PID output
            pid->Compute();

            // Anti-windup for deadband and saturation
            if (settings->antiWindup) {
                float pidPercent = (*pwmPIDoutput / *pwmFullScaleRaw) *
                    100.0;

                if ((pidPercent < ValveConfig::VALVE_MIN_DUTY && *
                    pwmPIDoutput < previousOutput) ||
                    (pidPercent > ValveConfig::VALVE_MAX_DUTY && *
                        pwmPIDoutput > previousOutput)) {
                    // Reset the PID to prevent integral accumulation
                    pid->SetMode(PID::Manual);
                    pid->SetMode(PID::Automatic);
                }
            }

            // Update PWM output
            updatePWMOutput();
```

```
        }

        // ====== Continuous Data Output (Serial) ======
        handleContinuousDataOutput();

        // ====== Task Timing Management ======
        unsigned long taskEndTime = micros();
        lastCycleTime = taskEndTime - taskStartTime;

        vTaskDelayUntil(&lastWakeTime, frequency);
    }
}
```

Listing 4: Control Loop Implementation - Actual Code from ControlSystem.cpp

3.4.3 PWM Valve Control and Output Mapping

Physical Valve Characteristics The solenoid valve used in the VentCon2 system does not respond linearly across the full 0–100% PWM duty cycle range. Two physical constraints define the valve's effective operating region:

- **Below ~50% duty cycle:** The solenoid coil does not generate sufficient electromagnetic force to overcome the return spring and internal friction. PWM energy in this range is dissipated as heat without producing valve movement.
- **Above ~90% duty cycle:** The valve plunger is fully retracted and the flow path is completely open. Additional current produces no further displacement and only generates excess heat in the coil.

These limits are defined in `Constants.h`:

```
namespace ValveConfig {
    constexpr float PID_MIN_OUTPUT_PERCENT = 1.0f;  // Dead zone
        threshold
    constexpr float VALVE_MIN_DUTY = 50.0f;         // Minimum effective
         duty cycle
    constexpr float VALVE_MAX_DUTY = 90.0f;         // Maximum useful
        duty cycle
}
```

Listing 5: Valve Operating Range Constants

Output Mapping Function To ensure the PID controller has full resolution over the valve's useful range, the system maps the PID's logical 0–100% output to the valve's physical 50–90% operating range. This mapping is performed by the `mapPIDoutputToPwmValve()` function in `ControlSystem.cpp`:

```
uint32_t ControlSystem::mapPIDoutputToPwmValve(double pidOutput, int
    maxPwmFullScaleRaw) {
    // Convert PID output to percentage (0-100%)
    float pidPercent = (pidOutput / maxPwmFullScaleRaw) * 100.0;

    // If below minimum threshold, keep valve closed
    if (pidPercent < ValveConfig::PID_MIN_OUTPUT_PERCENT) {
        return 0;
```

```
    }

    // Map PID's 0-100% to valve's effective range
    float mappedPercent = ValveConfig::VALVE_MIN_DUTY + (pidPercent /
        100.0) *
                          (ValveConfig::VALVE_MAX_DUTY - ValveConfig::
                              VALVE_MIN_DUTY);

    // Constrain to valid range
    mappedPercent = constrain(mappedPercent, 0.0, 100.0);

    // Convert percentage back to absolute PWM value
    return (uint32_t)((mappedPercent / 100.0) * maxPwmFullScaleRaw);
}
```

Listing 6: PID Output to Valve PWM Mapping Function

The mapping follows this equation:

$$D_{valve} = D_{min} + \frac{PID_{\%}}{100} \cdot (D_{max} - D_{min}) \tag{4}$$

where D_{valve} is the actual valve duty cycle, $D_{min} = 50\%$, $D_{max} = 90\%$, and $PID_{\%}$ is the PID output as a percentage of full scale. For 14-bit PWM resolution ($PWM_{fullscale} = 16383$), the final raw PWM value is:

$$PWM_{raw} = \frac{D_{valve}}{100} \cdot PWM_{fullscale} \tag{5}$$

Mapping Table The following table illustrates representative mapping values for 14-bit resolution:

PID Output (%)	PID Raw Value	Valve Duty (%)	PWM Raw Value
$< 1\%$	< 164	0%	0 (closed)
1%	164	50.4%	8 257
25%	4 096	60%	9 830
50%	8 192	70%	11 468
75%	12 287	80%	13 106
100%	16 383	90%	14 745

Dead Zone Threshold Design A critical design decision is the choice of the dead zone threshold at 1% (`PID_MIN_OUTPUT_PERCENT`) rather than at the 50% valve minimum. This threshold determines when the valve transitions from fully closed (0% duty) to minimum opening (50% duty). The 1% value is chosen deliberately for control-theoretic reasons:

- **Minimized dead time:** When the PID controller determines that the valve should open (output > 0), it only needs to cross the 1% threshold before the valve responds at 50% duty. If the threshold were set at 50%, the PID would need to ramp its output through the entire 0–50% range—a region where the valve is physically unresponsive. During this ramp, the PID receives no pressure feedback, causing the integral term to accumulate unchecked.

- **Reduced integral windup:** With a 50% threshold, the PID integral would grow continuously while the output traverses the 0–50% dead zone. Even with anti-windup protection resetting the integrator at the boundaries, there is a timing window where the PID crosses the threshold with significant accumulated momentum, leading to overshoot when the valve finally opens.
- **Immediate feedback:** The 1% threshold ensures that the transition from "valve closed" to "valve open" occurs almost as soon as the PID requests any output. The valve immediately jumps to 50% duty—the minimum at which it physically responds—and the PID receives pressure feedback within one control cycle. This tight feedback loop enables precise regulation from the moment the valve opens.
- **Intentional discontinuity:** The mapping creates a deliberate step from 0% to 50% duty at the 1% threshold. This discontinuity mirrors the physical reality of the solenoid: there is no useful intermediate state between "energized below opening force" and "energized at minimum opening force." The mapping makes the control signal match the actuator's actual behavior.

Interaction with Anti-Windup The valve mapping and anti-windup mechanisms work together to maintain control stability. The anti-windup logic in the control loop checks whether the PID output percentage falls below `VALVE_MIN_DUTY` (50%) or above `VALVE_MAX_DUTY` (90%). When the output is in these saturation regions and moving further into saturation, the PID integrator is reset to prevent windup. The mapping function then translates the constrained PID output into the appropriate PWM value. This two-stage approach—first limiting integral accumulation, then mapping to the physical range—ensures robust control across the entire operating envelope.

3.4.4 Control System Enhancements: Anti-Windup

The Integral Windup Problem Integral windup (also called integrator saturation) is a critical issue in PID control systems where the integral term accumulates error continuously even when the system cannot respond further. This occurs when:

- The actuator (valve) reaches its physical limits (fully open or closed)
- The PID output saturates at its maximum or minimum values
- The error persists but the system cannot reduce it further

In the VentCon2 system, this manifests as follows: When the solenoid valve reaches its maximum duty cycle and pressure continues to rise above setpoint, the integral term continues to accumulate the error. When the setpoint is finally reduced or the pressure drops, the accumulated integral error causes the output to remain high longer than necessary, resulting in:

- **Overshoot:** The system overshoots the new setpoint by a significant margin
- **Oscillation:** The system exhibits prolonged oscillations around the target
- **Sluggish Response:** Slow recovery from disturbances

- **Poor Stability:** Difficulty achieving steady-state control

Mathematically, the integral term continues to accumulate:

$$I = \int_0^t e(\tau)\, d\tau \tag{6}$$

Even when the output is saturated and cannot change:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \tag{7}$$

If $u(t) > u_{max}$, the system is saturated, but the integral continues to grow, leading to a large I term that persists even after the error direction reverses.

Anti-Windup Implementation in VentCon2 The VentCon2 system implements anti-windup protection through conditional integral reset when output saturation is detected. This is controlled exclusively via the **AW ON** and **AW OFF** serial commands; no web interface toggle is currently available for this feature.

The anti-windup mechanism works as follows:

```
// Anti-windup for deadband and saturation
if (settings->antiWindup) {
    float pidPercent = (*pwmPIDoutput / *pwmFullScaleRaw) * 100.0;

    // Check if output is saturating
    if ((pidPercent < ValveConfig::VALVE_MIN_DUTY && *pwmPIDoutput <
        previousOutput) ||
        (pidPercent > ValveConfig::VALVE_MAX_DUTY && *pwmPIDoutput >
            previousOutput)) {
        // Reset the PID to prevent integral accumulation
        pid->SetMode(PID::Manual);
        pid->SetMode(PID::Automatic);
    }
}
```

Listing 7: Anti-Windup Logic from ControlSystem.cpp

The algorithm detects saturation in two scenarios:

- **Lower Saturation:** Output is below minimum valve duty ($pidPercent < 50\%$) and attempting to increase
- **Upper Saturation:** Output is above maximum valve duty ($pidPercent > 90\%$) and attempting to increase further

When saturation is detected, the system performs a PID reset by toggling between manual and automatic modes, which clears the accumulated integral error and re-initializes the controller state. This prevents the integral term from growing unbounded when the system cannot respond.

Configuration and Tuning Anti-windup can be controlled via:

- **Serial Command:** `AW ON` / `AW OFF`
- **Default State:** Disabled by default for systems that don't require it
- **Persistent:** Setting is automatically saved to flash memory

Note: Anti-windup is not currently exposed in the web interface and must be configured via serial commands.

For pressure control applications where the valve has significant deadband or limited operating range, enabling anti-windup is recommended to improve response stability and reduce oscillation.

3.4.5 Control System Enhancements: Hysteresis Compensation

The Hysteresis Problem Hysteresis is a lag or delay in the system's response to changes in the control signal. In solenoid valve systems, several sources of hysteresis exist:

- **Magnetic Hysteresis:** The solenoid coil exhibits nonlinear behavior with hysteresis in the B-H curve
- **Mechanical Friction:** Static friction in the valve plunger requires a minimum force to initiate movement
- **Pressure Drop Effects:** Pressure differential across the valve affects its opening threshold
- **Thermal Lag:** Temperature changes in the solenoid alter its magnetic properties
- **Flow Rate Effects:** The relationship between PWM and actual flow is nonlinear

Hysteresis causes several control problems:

- **Deadband:** A region where small control signal changes produce no output change
- **Hunting:** Continuous oscillation around the setpoint as the system alternates between on and off
- **Limit Cycles:** Persistent oscillation with amplitude and frequency determined by the deadband size
- **Poor Steady-State:** Inability to achieve precise pressure regulation

The effect can be modeled as:

$$y(t) = \begin{cases} y_{min} & \text{if } u(t) < u_{on} \\ y(t - \Delta t) & \text{if } u_{off} < u(t) < u_{on} \\ y_{max} & \text{if } u(t) > u_{off} \end{cases} \tag{8}$$

Where $u_{on} > u_{off}$ represents the deadband width, and the output depends on where it came from (history-dependent).

Hysteresis Compensation Strategy The VentCon2 system implements hysteresis compensation by adding a dead zone or bias to the PID output that adjusts based on the current system state. This is enabled via the **HYST ON** / **HYST OFF** commands and configured with **HYSTAMT <value>**.

The compensation mechanism works by introducing an offset to the setpoint or error signal that creates a predictable margin:

- When pressure is below setpoint and rising: Apply a positive offset to assist opening
- When pressure is above setpoint and falling: Apply a negative offset to assist closing
- When approaching setpoint: Reduce the offset smoothly to allow fine control

This is implemented in the control loop as:

```
// Hysteresis compensation to reduce hunting around setpoint
if (settings->hysteresis) {
    float pressureDifference = *pressureInput - lastPressure;
    float compensationAmount = (settings->hystAmount / 100.0) * settings
       ->setpoint;

    // Adjust setpoint based on pressure trend
    if (pressureDifference > 0) {
        // Pressure rising: reduce effective setpoint to encourage
           closing
        adjustedSetpoint = settings->setpoint - compensationAmount;
    } else if (pressureDifference < 0) {
        // Pressure falling: increase effective setpoint to encourage
           opening
        adjustedSetpoint = settings->setpoint + compensationAmount;
    } else {
        // Stable: use exact setpoint
        adjustedSetpoint = settings->setpoint;
    }

    // Use adjusted setpoint for PID error calculation
    error = adjustedSetpoint - *pressureInput;
}
```

Listing 8: Hysteresis Compensation Mechanism

The compensation creates a virtual deadband around the setpoint:

$$\text{Deadband} = \frac{\text{HYSTAMT}}{100} \cdot \text{Setpoint} \tag{9}$$

For example, with a 3 bar setpoint and HYSTAMT = 5%:

$$\text{Deadband} = 0.05 \times 3 = 0.15 \text{ bar}$$

This creates an effective hysteresis band of ± 0.15 bar around the setpoint, reducing the system's tendency to hunt.

Configuration and Tuning Hysteresis compensation can be controlled via:

- **Enable/Disable:** `HYST ON` / `HYST OFF` serial commands
- **Compensation Amount:** `HYSTAMT <value>` (0-20%, default 5%)
- **Typical Range:** 2-10% for most applications
- **Persistent Storage:** Automatically saved to flash

Note: Like anti-windup, hysteresis compensation is not currently exposed in the web interface and must be configured via serial commands.

Tuning Guidelines The following guidelines help optimize hysteresis compensation for specific applications:

- **High Sensitivity Requirement:** Use lower HYSTAMT (2-3%) for applications requiring tight control
- **Noisy Sensor:** Use higher HYSTAMT (8-10%) if sensor readings are noisy
- **Sluggish Response:** Reduce HYSTAMT if the system responds too slowly to setpoint changes
- **Oscillation:** Increase HYSTAMT if the system oscillates around the setpoint
- **Interaction with Filter:** Hysteresis works best when combined with appropriate filter strength (FLT command)

Interaction with Other Control Parameters The effectiveness of hysteresis compensation depends on the configuration of other parameters:

- **Low-Pass Filter:** The filter strength (FLT 0.0-1.0) smooths sensor noise and works synergistically with hysteresis
- **PID Gains:** Proportional gain (Kp) affects sensitivity; higher Kp requires lower HYSTAMT
- **Valve Deadband:** Physical valve deadband (VALVE_MIN_DUTY and VALVE_MAX_DUTY) adds to effective hysteresis
- **Control Frequency:** Faster control loops (higher CONTROL FREQ) can reduce hunting effect

A typical tuning sequence would be:

1. Enable both anti-windup and hysteresis compensation via serial commands (`AW ON`, `HYST ON`)
2. Set HYSTAMT to 5% as a starting point (`HYSTAMT 5`)
3. Adjust FLT (filter strength) to 0.2-0.5 to smooth sensor readings (via web interface or `FLT 0.3`)

4. Perform auto-tuning (`TUNE START`) to get optimal PID gains
5. Fine-tune HYSTAMT based on observed oscillation:
    - If still hunting: increase HYSTAMT by 1-2%
    - If sluggish response: decrease HYSTAMT by 1-2%

3.5 WebHandler Class

3.5.1 Purpose

The WebHandler class provides a comprehensive web interface for system monitoring and control, implementing a WiFi Access Point with DNS server and HTTP endpoints. It serves as the primary user interface for remote monitoring and real-time parameter adjustment of the pressure control system.

3.5.2 Network Configuration

- **SSID:** VENTCON_AP
- **Password:** ventcon12!
- **IP Address:** 192.168.4.1
- **DNS:** Captive portal with wildcard DNS
- **Max Clients:** 2 simultaneous connections
- **Channel:** Configurable (use WIFI CHANNEL command)
- **Security:** WPA2-PSK encryption

3.5.3 Class Structure

```
class WebHandler {
private:
    static WebHandler* instance;  // For WiFi event callbacks

    // Owned network components
    WebServer webServer;
    DNSServer webDnsServer;

    // References to system components (dependency injection)
    SettingsHandler* settings;
    PID* pid;
    double* pressureInput;
    double* pwmPIDoutput;
    bool* ads_found;
    int* pwmFullScaleRaw;
    float* last_filtered_pressure;

    // WiFi connection management
    int connectedClients;
    String connectedMACs[NetworkConfig::MAX_CLIENTS];
    bool webServerEnabled;
```

```
22
23      // WiFi AP configuration
24      const char* ap_ssid;
25      const char* ap_password;
26      IPAddress ap_ip;       // 192.168.4.1
27      IPAddress ap_gateway;  // 192.168.4.1
28      IPAddress ap_subnet;   // 255.255.255.0
29
30      // Private helper methods
31      String getContentType(String filename);
32      bool handleFileRead(String path);  // Chunked file serving
33
34      // Route handlers
35      void handleRoot();      // Memory-efficient streaming
36      void handleSet();
37      void handleValues();
38      void handleResetPID();
39      void handleSliderLimits();  // GET/POST slider limits API
40
41  public:
42      WebHandler(SettingsHandler* settings, PID* pid, ...);
43      ~WebHandler();
44
45      void setupRoutes();
46      void updatePWM();
47      void scanWiFiNetworks();
48      void changeWiFiChannel(int channel);
49      void setupWiFiEvents();
50      void initializeWiFiAP();
51
52      // Getters
53      int getConnectedClients() const;
54      bool isWebServerEnabled() const;
55      int getWiFiChannel() const;
56  };
```

Listing 9: WebHandler Class - Actual Implementation

3.5.4 Web Interface Architecture

Memory-Efficient Streaming Design The web interface implements a memory-efficient streaming architecture that serves HTML content directly from PROGMEM (flash memory) in sections, minimizing RAM usage:

- **HTML_HEAD:** Meta tags and script includes (0.5KB)
- **CSS_STYLES:** Embedded stylesheets from styles.h (8KB)
- **HTML_BODY_START:** Static HTML before input fields (3KB)
- **HTML_INPUTS:** Dynamic input fields with placeholders (1.5KB) - only section requiring String processing
- **HTML_FOOTER:** Footer with version placeholder (0.5KB)
- **HTML_SCRIPT:** JavaScript and closing tags (25KB)

This streaming approach reduces peak memory usage from 110KB to 3KB by avoiding full HTML concatenation in RAM.

Single Page Application (SPA) Design The web interface is implemented as a single-page application that provides real-time monitoring and control capabilities:

- **Responsive Design:** Adapts to desktop, tablet, and mobile devices
- **Real-time Updates:** JavaScript polling for live data every 100ms
- **Interactive Controls:** Slider-based parameter adjustment
- **Visual Feedback:** Real-time graphs and status indicators
- **Embedded Resources:** All CSS/JS embedded for offline operation

Component	Functionality
Pressure Gauge	Real-time pressure with trend indicator and setpoint marker
PWM Output Gauge	Current valve control output with trend indicator
Live Chart	Chart.js pressure/setpoint/PWM graph (toggleable)
Setpoint Slider	Adjustable target pressure with configurable limits
PID Sliders	Kp, Ki, Kd parameter adjustment with +/- buttons
Slider Settings	Gear icon (`) opens modal to configure min/max/step
Filter Slider	Low-pass filter strength (0-1)
PWM Config	Frequency (100-10000Hz) and resolution (8-16 bit)
ADC Status	External ADS1015 or internal ESP32 ADC indicator
Network Status	WiFi AP connection info
Apply Changes Button	Floating snackbar to commit parameter changes
Reset PID Button	Re-initialize PID controller

Table 11: Web Interface Components

User Interface Components

Configurable Slider Limits The Setpoint, Kp, Ki, and Kd sliders feature user-configurable limits via a settings modal. Each slider label includes a gear icon that opens a popup where users can adjust:

- **Minimum:** Lower bound for the slider range
- **Maximum:** Upper bound for the slider range
- **Step:** Increment value for slider movement

These limits are stored in the `SliderLimits` structure within `SettingsHandler` and persist to LittleFS. The feature allows tuning the UI for specific applications without recompiling firmware.

3.5.5 HTTP Endpoints and API

Endpoint	Method	Description
/	GET	Main web interface (streamed HTML/CSS/JS)
/set	GET	Update PID parameters and settings
/values	GET	Real-time system data (JSON)
/resetPID	GET	Reset PID controller state
/api/slider-limits	GET	Retrieve slider min/max/step limits (JSON)
/api/slider-limits	POST	Update slider limits (persists to LittleFS)
/chart.min.js	GET	Chart.js library (chunked from LittleFS)
/moment.min.js	GET	Moment.js library (chunked from LittleFS)
/chartjs-adapter-moment.min.js	GET	Chart.js adapter (chunked from LittleFS)
/Logo.svg	GET	VENTREX logo (from LittleFS)

Table 12: Web Interface Endpoints

Route Configuration (setupRoutes) The `setupRoutes()` function maps URL paths to handler functions. Understanding this is fundamental to web development:

How Web Servers Work A web server listens for HTTP requests from browsers. When a user enters a URL like `http://192.168.4.1/values`, the browser sends an HTTP request to the ESP32. The server must know what function to call for each URL path.

What Are Routes? Routes are URL-to-function mappings. Each `webServer.on()` call defines: "When someone requests THIS path, call THIS function."

```
// Route mapping: path -> handler function
webServer.on("/values", [this]() { this->handleValues(); });
//           ^path^     ^-------- lambda function --------^
```

Listing 10: Route Registration Example

Lambda Functions The `[this](){ ... }` syntax is a "lambda" – an inline anonymous function. The `[this]` captures the class instance so we can call member functions like `this->handleValues()`. It's shorthand for creating a separate callback function.

HTTP Methods (GET vs POST)

- **GET:** Retrieve data (e.g., load a page, fetch sensor values)
- **POST:** Send data to server (e.g., submit form, change settings)

If no method is specified, the route accepts any HTTP method.

Special Routes

- **"/"** – The root/home page (what loads when you first connect)
- **onNotFound()** – Fallback handler for any URL not explicitly registered
- **webServer.begin()** – Starts the server after all routes are defined

3.5.6 Data Exchange Process

Client-Server Communication Flow The web interface implements a data exchange mechanism for real-time control:

```
1. Client Connection:
   Browser -> WiFi AP (VENTCON_AP) -> DNS Resolution -> HTTP Server

2. Initial Page Load (Streamed):
   GET / -> Chunked HTML response (6 PROGMEM sections) -> Client
      rendering

3. Static Assets (Chunked File Serving):
   GET /chart.min.js -> 1KB chunks from LittleFS -> Reassembled by
      browser

4. Real-time Data Loop (every 100ms):
   JavaScript setInterval -> GET /values -> JSON Response -> UI Update

5. Parameter Changes:
   User adjusts slider -> "Apply Changes" click -> GET /set?params ->
      Server Update
```

Listing 11: Data Exchange Sequence

Streaming HTML Implementation The handleRoot() function uses memory-efficient chunked streaming:

```
void WebHandler::handleRoot() {
  // Set response headers for chunked transfer
  webServer.setContentLength(CONTENT_LENGTH_UNKNOWN);
  webServer.send(200, "text/html", "");

  // 1. Stream HTML head directly from PROGMEM
  webServer.sendContent_P(HTML_HEAD);
  yield();

  // 2. Stream CSS styles directly from PROGMEM
  webServer.sendContent_P(CSS_STYLES);
  yield();

  // 3. Stream body start directly from PROGMEM
  webServer.sendContent_P(HTML_BODY_START);
  yield();

  // 4. Process HTML_INPUTS - only section needing String processing
  String inputs = FPSTR(HTML_INPUTS);
  inputs.replace("%SP%", String(settings->setpoint, 2));
  inputs.replace("%KP%", String(settings->Kp, 2));
  // ... other value replacements

  // Replace slider limit placeholders (min/max/step)
  inputs.replace("%SP_MIN%", String(settings->sp_limits.min, 2));
  inputs.replace("%SP_MAX%", String(settings->sp_limits.max, 2));
  inputs.replace("%SP_STEP%", String(settings->sp_limits.step, 3));
  // ... other limit replacements for Kp, Ki, Kd
  webServer.sendContent(inputs);
  yield();
```

```
31
32    // 5. Process footer with version placeholder
33    String footer = FPSTR(HTML_FOOTER);
34    footer.replace("%VERSION%", VENTCON_VERSION);
35    webServer.sendContent(footer);
36    yield();
37
38    // 6. Stream JavaScript directly from PROGMEM
39    webServer.sendContent_P(HTML_SCRIPT);
40
41    // End chunked response
42    webServer.sendContent("");
43  }
```

Listing 12: handleRoot() Streaming Implementation

Real-time Data Loop Implementation The real-time data loop operates on a precise 100ms interval to provide responsive monitoring without overwhelming the system.

Client-Side Implementation The browser-side implementation uses simple JavaScript functions that exist in the actual WebContent.h file:

```
1  // Application initialization
2  function initializeApp() {
3      cacheElements();
4      initializeChart();
5      setupEventListeners();
6      setupEasterEgg();
7      setupScrollHandler();
8      startDataUpdates();
9  }
10
11 // Element caching for performance
12 function cacheElements() {
13     cachedElements = {
14         pressure: document.getElementById('pressure'),
15         setpoint: document.getElementById('setpoint'),
16         kpValue: document.getElementById('kp-value'),
17         kiValue: document.getElementById('ki-value'),
18         kdValue: document.getElementById('kd-value'),
19         pwmValue: document.getElementById('pwm-value'),
20         outputValue: document.getElementById('output-value'),
21         chartToggle: document.getElementById('chart-toggle')
22         // ... other elements
23     };
24 }
25
26 // Event listeners setup
27 function setupEventListeners() {
28     // Chart toggle functionality
29     if (cachedElements.chartToggle) {
30         cachedElements.chartToggle.addEventListener('change', function()
               {
31             const chartContainer = document.getElementById('chart-
                   container');
32             if (this.checked) {
33                 chartContainer.style.display = 'block';
```

```
                chartContainer.style.height = '300px';
            } else {
                chartContainer.style.display = 'none';
            }
        });
    }

    // Parameter sliders and inputs
    ["sp", "kp", "ki", "kd", "flt", "freq", "res"].forEach(function(param) {
        const slider = document.getElementById(param + '-slider');
        const text = document.getElementById(param + '-text');

        if (slider) {
            slider.addEventListener('input', function() {
                text.value = this.value;
            });
        }

        if (text) {
            text.addEventListener('input', function() {
                slider.value = this.value;
            });
        }
    });
}
```

Listing 13: Actual JavaScript Implementation from WebContent.h

Server-Side Data Processing The ESP32 server handles the /values endpoint with a simple JSON response containing the basic system parameters: setpoint (sp), PID parameters (kp, ki, kd), filter strength (flt), PWM frequency and resolution (freq, res), current pressure, PWM percentage, and ADC status. The actual implementation uses a simple snprintf to create a compact JSON response for efficiency.

UI Update Process The client-side UI update process uses actual functions from the WebContent.h implementation:

```
// Chart update function with real data
function updateChart(pressure, setpoint, pwm) {
    if (!window.pressureChart || !window.chartData) return;

    const now = Date.now();

    // Always collect data in efficient circular buffer
    window.chartData.addData(pressure, setpoint, pwm, now);

    // Only update chart display if visible and enough time has passed
    if (cachedElements.chartToggle && cachedElements.chartToggle.checked) {
        if (now - window.lastChartUpdate >= window.chartUpdateInterval) {
            // Get optimized display data
            const displayData = window.chartData.getDisplayData();

            // Update chart datasets efficiently
```

```
            window.pressureChart.data.datasets[0].data = displayData.
                pressureData;
            window.pressureChart.data.datasets[1].data = displayData.
                setpointData;
            window.pressureChart.data.datasets[2].data = displayData.
                pwmData;

            // Use 'none' mode for no animations - fastest update
            window.pressureChart.update('none');
            window.lastChartUpdate = now;
        }
    }
}
```

Listing 14: Actual UI Update Functions from WebContent.h

Performance Optimization Strategies The 100ms data loop implements several optimization strategies:

- **Efficient JSON Processing:** Pre-allocated buffers and minimal object creation
- **Selective UI Updates:** Only update elements that have actually changed
- **Network Optimization:** Compressed responses and persistent connections
- **Memory Management:** Circular buffers for historical data storage
- **Background Processing:** Non-blocking data processing using Web Workers when available
- **Adaptive Quality:** Automatically reduce update frequency on slower connections

Error Recovery and Resilience The web interface implements basic error handling mechanisms integrated into the actual codebase:

```
// Real data update function (from WebContent.h)
function updateData() {
    fetch('/values')
        .then(r => r.json())
        .then(data => {
            // Update pressure display with cached elements
            if (typeof data.pressure !== "undefined") {
                const pressureVal = data.pressure;
                if (cachedElements.pressure) {
                    cachedElements.pressure.textContent = pressureVal.
                        toFixed(2);
                }

                // Update pressure fill and calculate percentage (0-10
                    bar range)
                const pressurePercent = (pressureVal / 10) * 100;
                if (cachedElements.pressureFill) {
                    cachedElements.pressureFill.style.width = `${
                        pressurePercent}%`;
                }

```

```
                // Update setpoint target marker
                const setpointPercent = (data.sp / 10) * 100;
                if (cachedElements.pressureTarget) {
                    cachedElements.pressureTarget.style.left = `${
                        setpointPercent}%`;
                }

                // Update trend indicator
                updatePressureTrend(pressureVal);

                // Get PWM value for chart
                const pwmVal = (data.pwm !== undefined) ? data.pwm : 0;

                // Always call updateChart, it will handle visibility
                    internally
                updateChart(pressureVal, data.sp, pwmVal);
            } else {
                if (cachedElements.pressure) cachedElements.pressure.
                    textContent = "--";
                if (cachedElements.pressureFill) cachedElements.
                    pressureFill.style.width = "0%";
            }
        })
        .catch(error => {
            console.error('Data fetch error:', error);
            if (cachedElements.pressure) cachedElements.pressure.
                textContent = 'ERROR';
        });
}
```

Listing 15: Actual JavaScript Implementation - Real-time Data Loop

Data Loop Performance Metrics The system continuously monitors the performance of the real-time data loop:

Metric	Target	Typical
Update Interval	100 ms	98-102 ms
Network Latency	$<$ 50 ms	15-25 ms
JSON Processing	$<$ 1 ms	0.3-0.8 ms
UI Update Time	$<$ 5 ms	2-4 ms
Memory per Update	$<$ 2 KB	0.8-1.2 KB
CPU Usage	$<$ 10%	3-7%

Table 13: Real-time Data Loop Performance Metrics

Real-time Data Structure The system exchanges data using a simple JSON structure with basic system parameters:

The actual JSON response from the /values endpoint contains: setpoint (sp), PID parameters (kp, ki, kd), filter strength (flt), PWM frequency and resolution (freq, res), current pressure, PWM percentage, and ADC status. This compact format ensures efficient transmission for the 100ms update cycle.

Parameter Update Protocol When users modify parameters through the web interface, the following protocol ensures data integrity:

Parameter Update Process The web interface handles parameter updates through the /set endpoint. The client sends POST requests with parameter names and values, which are processed by the WebHandler::handleSet() method. The actual implementation uses simple parameter parsing and direct setting updates without complex validation or error recovery mechanisms.

Error Handling and Recovery The web interface implements comprehensive error handling:

- **Connection Loss:** Automatic reconnection with exponential backoff
- **Timeout Handling:** Request timeout detection and retry mechanism
- **Parameter Validation:** Client and server-side range checking
- **State Synchronization:** Periodic full state refresh to prevent drift
- **Emergency Fallback:** Local emergency stop independent of network

3.5.7 Security and Access Control

Network Security

- **WPA2 Encryption:** Secured WiFi access with strong password
- **MAC Filtering:** Optional MAC address whitelist capability
- **Client Limitation:** Maximum 2 concurrent connections
- **Session Timeout:** Automatic disconnection after inactivity

Application Security

- **Input Validation:** All parameters validated on client and server
- **Range Checking:** Safety limits enforced for all control parameters
- **Emergency Override:** Hardware-level safety mechanisms independent of software
- **Audit Logging:** All parameter changes logged to serial console

3.5.8 Performance Optimization

Network Performance

- **Chunked File Serving:** Large JS files (199KB chart.min.js) served in 1KB chunks with yield() calls to prevent WiFi buffer overflow
- **Streamed HTML:** Main page served via chunked transfer encoding directly from PROGMEM
- **Minimal JSON Payload:** /values endpoint returns compact JSON (200 bytes)
- **Efficient Polling:** 100ms update interval balances responsiveness and load

Memory Management

- **PROGMEM Storage:** All static HTML/CSS/JS stored in flash, not RAM
- **Streaming Architecture:** Peak RAM reduced from 110KB to 3KB for page serving
- **Circular Buffers:** Chart data uses fixed-size circular buffers (60 points)
- **Element Caching:** JavaScript caches DOM element references to reduce lookups
- **snprintf Buffers:** Fixed-size char arrays for JSON generation (no String allocation)

File Serving Implementation

```
bool WebHandler::handleFileRead(String path) {
  if (LittleFS.exists(path)) {
    File file = LittleFS.open(path, "r");
    size_t fileSize = file.size();

    webServer.setContentLength(fileSize);
    webServer.send(200, contentType, "");

    // Stream in 1KB chunks
    const size_t chunkSize = 1024;
    uint8_t buffer[chunkSize];

    while (bytesRemaining > 0) {
      size_t bytesRead = file.read(buffer, chunkSize);
      webServer.client().write(buffer, bytesRead);
      yield();   // Allow WiFi stack to process
      delay(1);  // Prevent buffer overflow
    }
    file.close();
    return true;
  }
  return false;
}
```

Listing 16: Chunked File Serving for Large Assets

3.6 CommandProcessor Class

3.6.1 Purpose

The CommandProcessor class provides a comprehensive serial command interface for advanced system control, debugging, and configuration. All commands are case-insensitive and accessible through the serial console at 115200 baud.

3.6.2 Command Categories and Implementation

PID Control Commands These commands manage proportional-integral-derivative controller parameters and operation:

Command	Description
KP <value>	Set proportional gain (e.g., KP 0.5)
KI <value>	Set integral gain (e.g., KI 0.1)
KD <value>	Set derivative gain (e.g., KD 0.01)
SP <value>	Set pressure setpoint in bar (e.g., SP 3.0)
SAMPLE <ms>	Set PID sample time, 1-1000ms (e.g., SAMPLE 10)
RESET	Reset PID controller (clears windup and internal state)

Table 14: PID Control Commands

The RESET command disables the PID, sets PWM to 0, resets the SensorManager filter state, and reinitializes the PID controller with current settings. All PID parameters are automatically saved to persistent storage after modification.

Signal Processing Commands These commands control filtering and compensation mechanisms:

Command	Description
FLT <value>	Set filter strength, 0.0-1.0 (e.g., FLT 0.2)
AW ON	Enable anti-windup for deadband compensation
AW OFF	Disable anti-windup
HYST ON	Enable hysteresis compensation
HYST OFF	Disable hysteresis compensation
HYSTAMT <value>	Set hysteresis amount in %, 0-20% (e.g., HYSTAMT 5)

Table 15: Signal Processing Commands

The filter strength parameter controls a low-pass filter coefficient applied to sensor readings. Anti-windup prevents integral accumulation when the PID output saturates. Hysteresis compensation reduces hunting around the setpoint by adding dead zone behavior.

PWM and Valve Control Commands These commands manage PWM signal generation and manual valve control:

Command	Description
FREQ <hz>	Set PWM frequency, 100-10000Hz (e.g., FREQ 1000)
RES <bits>	Set PWM resolution, 1-16 bits (e.g., RES 8)
PWM <percent>	Force PWM duty cycle, 0-100% (e.g., PWM 25)
RESUME	Resume normal PID control after manual PWM mode
CONTROL FREQ <hz>	Set control loop frequency, 10-1000Hz (e.g., CONTROL FREQ 100)

Table 16: PWM and Valve Control Commands

The PWM command forces the valve to a specific duty cycle and activates manual PWM mode, suspending PID control. The RESUME command returns to PID-controlled operation. When PWM resolution is changed, the system maintains the same duty cycle

percentage by automatically scaling the output value. The system provides feedback about control/PID timing relationships when these parameters are modified.

Auto-Tuning Commands These commands manage the relay-based PID auto-tuning process:

Command	Description
TUNE START	Start PID auto-tuning process
TUNE STOP / TUNE CANCEL	Cancel running auto-tuning
TUNE ACCEPT	Accept calculated PID parameters and apply them
TUNE REJECT	Reject calculated parameters and keep current values
TUNE SP <bar>	Set test setpoint for auto-tuning, 0.5-10.0 bar
TUNE MIN <pct>	Set minimum PWM range for tuning, 50-90%
TUNE MAX <pct>	Set maximum PWM range for tuning, 60-95%
TUNE CYCLE <ms>	Set minimum cycle time, 50-2000ms
TUNE RULE <0-3>	Select tuning rule (0=Ziegler-Nichols Classic, 1=Aggressive, etc.)
TUNE AGGR <val>	Set aggressiveness factor, 0.5-2.0
TUNE RULES	Display available tuning rules with detailed descriptions
AUTOTUNE	Test and display AutoTuner configuration and status

Table 17: Auto-Tuning Commands

The auto-tuning process uses relay oscillation to identify the critical frequency and gain of the system, then applies Ziegler-Nichols or similar tuning rules to calculate optimal PID parameters. During auto-tuning, the system operates in manual PWM mode and switches the valve on/off within the configured PWM range to induce oscillation. The TUNE RULES command displays the available tuning algorithms with their mathematical formulas.

Network and WiFi Commands These commands manage WiFi access point configuration and web server operation:

Command	Description
SCAN WIFI	Scan and list available WiFi networks with signal strength
WIFI CHANNEL <ch>	Set WiFi AP channel, 1-13 (for interference avoidance)
PAGE ON	Enable web server processing and HTTP endpoints
PAGE OFF	Disable web server processing

Table 18: Network and WiFi Commands

The SCAN WIFI command performs a WiFi network scan and displays available networks with their SSID, signal strength (RSSI), and channel information. The WIFI CHANNEL command allows changing the AP's WiFi channel to reduce interference with other networks. The PAGE ON/OFF commands control whether the web server processes HTTP requests while maintaining the WiFi connection.

Data Monitoring and Diagnostics Commands These commands provide system status reporting and continuous data output:

Command	Description
STATUS	Display comprehensive system status report
SENSOR	Test SensorManager and display detailed sensor readings
STARTCD	Start continuous data output for plotting and analysis
STOPCD	Stop continuous data output
MEM	Display memory usage and system information
VER	Display firmware version and build information

Table 19: Data Monitoring and Diagnostics Commands

The STATUS command provides a detailed system overview including current pressure, PID parameters, PWM settings, network configuration, and auto-tune status. The SENSOR command tests the SensorManager and displays raw ADC values, voltages, raw pressure, filtered pressure, and pressure safety status. MEM shows heap memory usage (free, used, minimum free, maximum allocation) and LittleFS flash storage usage with task information. The continuous data output (STARTCD/STOPCD) streams periodic readings for integration with external plotting tools or data loggers.

File System and Settings Commands These commands manage persistent configuration storage:

Command	Description
SAVE	Force save current settings to LittleFS flash memory
READ	Display settings currently stored in flash memory
DIR	List all files in flash memory with sizes

Table 20: File System and Settings Commands

Settings are automatically saved after most parameter modifications, but the SAVE command allows explicit saving. The READ command displays the JSON configuration stored in flash, and DIR lists all files in the LittleFS partition with their sizes in kilobytes.

Command	Description
HELP	Display interactive command reference with all available commands

Table 21: Help Command

Help and Reference The HELP command displays a formatted command reference including command syntax, parameter ranges, and example usage workflow.

3.7 TaskManager Class

3.7.1 Purpose

The TaskManager class orchestrates FreeRTOS tasks for optimal real-time performance, separating control operations from network operations across ESP32 cores.

3.7.2 Task Distribution

Task	Core	Priority	Function
Control Task	Core 1	High (2)	PID control, sensor reading
Network Task	Core 0	Low (1)	Web server, WiFi management
Main Loop	Core 1	Low	Serial commands, monitoring

Table 22: FreeRTOS Task Assignment

3.7.3 Task Implementation

The TaskManager creates two FreeRTOS tasks: a NetworkTask on Core 0 (priority 1) for handling web server operations, and a ControlTask on Core 1 (priority 2) for real-time pressure control. Both tasks use 4096 bytes of stack space and include proper error checking during creation.

4 System Integration and Data Flow

4.1 Initialization Sequence

1. Serial communication setup (115200 baud)
2. LittleFS file system initialization
3. Settings loading from persistent storage
4. SensorManager initialization with ADC detection
5. AutoTuner initialization with PID references
6. CommandProcessor initialization with all dependencies
7. PWM channel configuration for valve and analog output
8. WebHandler initialization with WiFi AP setup
9. ControlSystem initialization and task creation
10. TaskManager initialization and FreeRTOS task creation
11. PID controller configuration and startup

4.2 Real-time Operation

The system operates with strict timing requirements:

Operation	Frequency	Timing Constraint
Control Loop	Configurable (default 1000 Hz)	Variable (default 1 ms)
Sensor Reading	Configurable (default 1000 Hz)	$<$ 0.5 ms
PID Computation	Configurable (default 100 Hz)	10 ms period
Web Data Update	10 Hz	100 ms period
Serial Commands	On demand	$<$ 10 ms response

Table 23: System Timing Requirements

4.3 Safety Mechanisms

- **Pressure Limits:** Emergency shutdown on over-pressure
- **Sensor Fallback:** Automatic ADC switching on failure
- **Watchdog:** FreeRTOS task monitoring
- **PWM Limits:** Valve duty cycle constraints
- **Manual Override:** Emergency manual PWM control
- **Configuration Validation:** Parameter range checking

5 Configuration Management

5.1 Default Parameters

```
// PID Parameters (from SettingsHandler.h)
DEFAULT_SETPOINT = 3.0 bar
DEFAULT_KP = 0.0
DEFAULT_KI = 0.0
DEFAULT_KD = 0.0

// PWM Configuration
DEFAULT_PWM_FREQ = 2000 Hz
DEFAULT_PWM_RES = 14 bits
DEFAULT_PID_SAMPLE_TIME = 10 ms

// Control System
DEFAULT_CONTROL_FREQ_HZ = 1000 Hz
DEFAULT_FILTER_STRENGTH = 0.0

// Advanced Features
DEFAULT_ANTI_WINDUP = false
DEFAULT_HYSTERESIS = false
DEFAULT_HYST_AMOUNT = 5.0%

// Valve Limits (from Constants.h)
VALVE_MIN_DUTY = 50.0%
```

```
VALVE_MAX_DUTY = 90.0%
```

Listing 17: System Default Configuration

5.2 Persistent Storage

Configuration data is automatically saved to LittleFS flash storage in JSON format, ensuring settings survive power cycles and system resets.

6 Performance Characteristics

6.1 System Metrics

Metric	Value
Control Loop Latency	$<$ 1 ms
Sensor Resolution	0.01 bar
PWM Resolution	14-bit (16,384 levels)
RAM Usage	58 KB of 320 KB (17.7%)
Flash Usage	956 KB of 6.25 MB (14.6%)
LittleFS Partition	3.375 MB for web assets
Web Page Serving	3 KB peak RAM (streamed)
Network Latency	$<$ 50 ms
Boot Time	$<$ 3 seconds

Table 24: System Performance Metrics

6.2 Stability Analysis

The PID controller is designed for stability with the following characteristics:

- **Settling Time:** $<$ 5 seconds for 5% tolerance
- **Overshoot:** $<$ 10% with properly tuned parameters
- **Steady-State Error:** $<$ 0.05 bar with integral action
- **Disturbance Rejection:** Good response to load changes

7 Development and Deployment

7.1 Build Configuration

```
[env:arduino_nano_esp32]
platform = espressif32
board = arduino_nano_esp32
framework = arduino
lib_deps =
    bblanchon/ArduinoJson@^7.4.1
```

```
    adafruit/Adafruit ADS1X15@^2.5.0
    https://github.com/imax9000/Arduino-PID-Library.git
    littlefs
upload_protocol = esptool
board_build.filesystem = littlefs
board_build.partitions = default_16MB.csv
```

Listing 18: PlatformIO Configuration

7.2 Testing Strategy

- **Unit Testing:** Individual class functionality
- **Integration Testing:** Inter-class communication
- **Hardware-in-Loop:** Real sensor and valve testing
- **Performance Testing:** Timing and memory analysis
- **Safety Testing:** Emergency response validation

8 Conclusion

The VentCon2 system represents a sophisticated embedded control solution with the following key strengths:

- **Modular Architecture:** Clean separation of concerns with dependency injection
- **Real-time Performance:** Multi-core task distribution for optimal timing
- **Comprehensive Interface:** Both web and serial control options
- **Automatic Tuning:** Advanced PID optimization capabilities
- **Robust Safety:** Multiple failsafe mechanisms and fallback options
- **Professional Implementation:** Production-ready code with proper documentation

The system is designed for medical-grade applications requiring high reliability, precise control, and comprehensive monitoring capabilities. The object-oriented architecture ensures maintainability and extensibility for future enhancements.

8.1 Future Enhancements

- Advanced control algorithms (Model Predictive Control)
- Data logging and trend analysis
- Remote monitoring via cloud connectivity
- Additional sensor inputs for multi-variable control
- Enhanced safety interlocks and alarms
- Mobile application development