

ROOM REVERB PLUGIN: SOFTWARE SPECIFICATION

1. INTRODUCTION

This Software Specification defines the design and implementation details for RoomReverbPlugin. It accompanies the Requirements Document and provides sufficient detail for development, testing, and maintenance.

Objectives:

- Define the architecture, modules, and interfaces used to satisfy the Functional and Non-Functional Requirements (FR/NFR).
- Specify algorithms, data models, threading, and error handling strategies.
- Standardise parameters, ranges, defaults, and persistence formats for cross-platform builds (VST3 + Standalone).

1.1 REFERENCES

- RoomReverbPlugin Requirements Document (latest).
- Repository README.md and JUCE project file (.jucer).
- JUCE documentation: AudioProcessor, AudioProcessorEditor, dsp::Convolution, AudioDeviceManager.
- WAV file format (IEEE float 32-bit).

1.2 DEFINITIONS & ACRONYMS

Term	Definition
IR	Impulse Response — the time-domain response generated by the simulation.
HRTF	Head-Related Transfer Function — used for binaural rendering.
PRNG	Pseudo-Random Number Generator — seeded to ensure determinism.
SR	Sample Rate — the host or selected sample rate for IR generation.

2. SYSTEM OVERVIEW

RoomReverbPlugin consists of a JUCE AudioProcessor/AudioProcessorEditor pair, an acoustic model for a rectangular room, a two-pass ray/path tracing engine, IR synthesis/export pipeline, an optional preview convolver, and a first-person 3D view. The same code base builds as a VST3 plug-in and as a Standalone application.

3. ARCHITECTURE

3.1 COMPONENT RESPONSIBILITIES

Component	Responsibilities	Key Interfaces
PluginProcessor	Owns audio I/O, parameter layout, background job orchestration; hosts optional preview convolver; reports latency.	AudioProcessor, ValueTree; RoomModel; TraceEngine; IRSynth
PluginEditor	Hosts all controls and the 3D view; shows progress/cancel and diagnostics/log panels.	Processor parameters; Diagnostics; 3DView
RoomModel	Stores geometry (width/length/height), surface absorption (six planes), source/listener positions, environment (temperature).	Public getters/setters; validation
TraceEngine	Generates rays, computes reflections against axis-aligned planes, accumulates successful paths (time-of-flight, gain).	RoomModel; thread pool; PRNG; callbacks
IRSynth	Bins arrivals into an IR buffer at SR; applies headroom normalisation and optional window/gate.	Trace results; AudioSampleBuffer
IRExport	Writes IR to 32-bit float WAV using a templated filename; handles file I/O errors.	WAVWriter; filesystem
Diagnostics	Collects and displays metrics: rays, paths, est. RT60, CPU/GPU, memory; logging sink.	Logger; UI overlay
Integrations	Adapters for dsp::Convolution preview, 3D sound engine/SAF, optional GPU kernels.	Compile-time flags; runtime toggles

3.2 THREADING MODEL

- Audio Thread: real-time safe; processes input → (optional) convolver → output. Never allocates or blocks.
- Message Thread: UI updates, parameter changes, progress/log display.
- Worker Threads: tracing and IR synthesis; cancellable jobs posting progress to the UI.
- GPU (optional): batched intersection kernels; CPU fallback if unavailable.

3.3 DATA FLOW

Parameters → RoomModel → TraceEngine (Pass 1 discovery → Pass 2 refinement) → IRSynth (IR buffer) → IRExport (WAV). When preview is enabled: Latest IR → dsp::Convolution → Audio output (with host latency reported).

4. DETAILED DESIGN

4.1 PARAMETERS

ID	Name	Type	Range / Enum	Default	Automatable	Notes
P-001	Room Width (m)	float	0.5 – 50.0	6.0	Yes	Clamped; updates geometry/3D view
P-002	Room Length (m)	float	0.5 – 50.0	8.0	Yes	Clamped; updates geometry/3D view
P-003	Room Height (m)	float	0.5 – 20.0	3.0	Yes	Clamped; updates geometry/3D view
P-004	Absorption (Wall +X)	float	0.0 – 1.0	0.2	Yes	Similarly for -X, +Y, -Y, +Z ceiling, -Z floor
P-005	Source X (m)	float	0 – width	1.0	Yes	Inside bounds
P-006	Source Y (m)	float	0 – length	1.0	Yes	Inside bounds
P-007	Source Z (m)	float	0 – height	1.2	Yes	Inside bounds
P-008	Listener X (m)	float	0 – width	4.0	Yes	Inside bounds
P-009	Listener Y (m)	float	0 – length	6.0	Yes	Inside bounds
P-010	Listener Z (m)	float	0 – height	1.2	Yes	Inside bounds
P-011	Max Reflection Order	int	1 – 12	6	No	Higher order → more paths/compute
P-012	Ray Count	int	1k – 500k	100k	No	Total rays for Pass 1 (Pass 2 scales around hits)

P-013	Random Seed	uint32	0 – 2 ³² -1	123456789	No	Deterministic runs
P-014	IR Length (s)	float	0.5 – 10.0	3.0	No	Buffer duration
P-015	Headroom (dBFS)	float	-24 – 0	-6	No	Target peak after normalisation
P-016	Window Type	enum	None, Hann, Tukey	Hann	No	Tail window
P-017	Window Amount	float	0.0 – 1.0	0.2	No	Tukey alpha or fade strength
P-018	Gate Threshold (dBFS)	float	-120 – -40	-80	No	Optional noise gate on tail
P-019	Channel Format	enum	Mono, Stereo, Binaural	Mono	No	Binaural requires 3D engine/HRTF
P-020	Preview Enable	bool	Off/On	Off	No	Convolve input with latest IR
P-021	Wet/Dry Mix	float	0.0 – 1.0	0.5	Yes	Active when preview enabled
P-022	Quality Level	enum	Low, Medium, High	Medium	No	Affects 3D view settings
P-023	Interactive Mode	bool	Off/On	Off	No	Debounced IR generation for live tweaks
P-024	Interactive Debounce (ms)	int	100 – 1000	300	No	Delay before regenerating IR
P-025	Threads	int	Auto / 1–16	Auto	No	Worker thread pool size
P-026	GPU Enable	bool	Off/On	Off	No	Optional GPU path

P-027	Diagnostics Toggle	bool	Off/On	On	No	Show overlay
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4.2 ALGORITHMS

- Pass 1 — Discovery: Emit N rays from source with uniform random directions (seeded PRNG). Compute specular reflections against the six planes (axis-aligned box). Each hit applies per-surface absorption; path accumulates gain and travel time. Terminate when reflection order limit reached or cumulative gain < epsilon.
- Select successful paths (those intersecting a listener acceptance volume or contributing above a gain threshold). Store hit sequences (surface indices, times, gains).
- Pass 2 — Refinement: Importance-sample new rays around discovered directions to reduce variance; update path statistics.
- IR Synthesis:
 - Bin each path's arrival time into a discrete sample index at the current SR; add weighted amplitude.
 - Apply optional window (Hann/Tukey) to late tail and optional gate below threshold.
 - Normalise/peak-limit to headroom target (−6 dBFS default).
- Listener Model:
 - Mono: point microphone at listener position; inverse-square distance implicit in path gain.
 - Stereo/Binaural: when enabled, map paths through HRTF/3D engine; channel routing handled in IRSynth.

4.3 DATA MODELS

Entity	Fields	Notes
RoomModel	width, length, height; absorption[6]; tempC; src{x,y,z}; lis{x,y,z}	All lengths in meters; absorption 0..1
PathHit	surfaceIndex; point{x,y,z}; distance; timeSec; gain	Reflection bookkeeping; used by IRSynth
IRBuffer	sampleRate; lengthSec; samples[] (float)	32-bit float buffer; mono or stereo

4.4 PERSISTENCE & STATE

State is stored in a JUCE ValueTree and serialised via APVTS (AudioProcessorValueTreeState). Preset files include all parameters and positions. Standalone builds persist to user settings.

Suggested JSON shape for debug/export:

```
{ "version": 1, "room": { "w": 6, "l": 8, "h": 3, "abs": [0.2, 0.2, 0.2, 0.2, 0.1, 0.3], "src": [1, 1, 1.2], "lis": [4, 6, 1.2],  
  "trace": { "order": 6, "rays": 100000, "seed": 123456789, "ir": { "len": 3.0, "headroom": -  
6, "window": "Hann", "alpha": 0.2, "gateDb": -80, "format": "Mono", "preview": { "enabled": false, "mix": 0.5 } }
```

4.5 FILE FORMATS

- IR Export (WAV 32-bit float): sample rate equals host SR by default; channel count 1 or 2.
- Filename template: RoomReverb_{date}_{sr}_{len}s_{fmt}.wav; safe characters only.

4.6 UI SPECIFICATION

- Left panel: Room controls (size, absorption), Source/Listener positions, Trace settings (order, rays, seed).
- Bottom bar: Process / Cancel buttons, progress %, ETA, and a log console.
- Right panel: IR settings (length, headroom, window/gate), Export button and path selector.
- Top toolbar: Preview toggle, Wet/Dry, Diagnostics toggle, Quality selector.
- Main canvas: First-person 3D view with WASD + mouse-look; optional grid and axis gizmo.
- W/A/S/D to move; mouse to look; Shift to sprint; R/F to move up/down.
- Arrow keys to nudge source/listener when selected; Ctrl to snap to 0.1 m increments.

4.7 ERROR HANDLING & LOGGING

- All file and compute errors are logged to a non-modal console with severity (Info/Warning/Error).
- Export failures provide a retry and 'Open Folder' action; tracing failures suggest reducing ray count/order.
- Assertions are disabled in release builds; parameter validation prevents invalid states.

4.8 PERFORMANCE TARGETS

- Audio callback (preview off): no allocations; peak callback time < 50% of buffer time at 128-sample buffer.
- Tracing throughput: document rays/sec across budgets; scaling $\geq 80\%$ of ideal up to 8 cores.
- GPU mode (if compiled): $\geq 2\times$ throughput on reference device.

5. BUILD & DEPLOYMENT

- Build system: JUCE Projucer (.jucer) primary; optional CMake equivalent.
- Targets: VST3, Standalone. Ensure Standalone target enabled in Projucer or FORMATS includes Standalone in CMake.
- Artifacts: .vst3 bundle and .exe/.app for Standalone; versioned via git tag or CI variable.
- Licensing: GPL v3 by default; commercial option available (LICENSE-COMMERCIAL).

6. SECURITY & PRIVACY

No network I/O or telemetry by default. File writes occur only on explicit export.

7. TESTABILITY HOOKS

- Headless '--render-ir' CLI for Standalone (optional) to generate IRs for CI comparisons.
- Golden-master IR sets per preset and sample rate; tolerance configurable in tests.
- Debug builds expose extra diagnostics counters and validation asserts.

8. TRACEABILITY

Each specification item maps to FR/NFR IDs in the Requirements Document. Example: Parameters (4.1) → FR-001..FR-005, FR-011..FR-013; Threading Model (3.2) → NFR-001..NFR-005; File Formats (4.5) → FR-013, FR-031.

9. APPENDIX A — DEFAULT PRESETS (SUGGESTED)

Preset	Settings
Small Booth	W=2.5 L=3.0 H=2.4; abs walls 0.3/ceil 0.2/floor 0.4; order 6; rays 60k; IR 1.5 s
Project Studio	W=4.0 L=6.0 H=2.8; abs 0.25; order 8; rays 120k; IR 2.0 s
Live Room	W=7.0 L=9.0 H=3.5; abs 0.18; order 8; rays 200k; IR 2.8 s
Hall	W=14.0 L=22.0 H=9.0; abs 0.1; order 10; rays 400k; IR 4.5 s