

AUTOMATIC MUSIC-REACTIVE LIGHTING SYSTEM

Design Document

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1. Introduction

1.1 Problem and Solution

Small venues, student events, home listening spaces, and interactive installations can benefit from lighting that responds to music in real time. Professional show-lighting systems can create sophisticated effects, but they typically require a separate controller, manually programmed cues, or a dedicated operator. Low-cost sound-active lights are simpler, but many respond primarily to instantaneous sound level and give little control over how pitch, rhythm, loudness, and physical motion are translated into a repeatable visual response. Our goal is to create a compact standalone system that analyzes a music signal in real time and generates synchronized RGBW lighting and motion without a cloud service or manually authored light show.

The proposed system receives a direct analog audio signal through a 3.5 mm stereo input. A passive splitter allows the same music source to feed both an external speaker and the lighting system, so the audience hears the normal source while the custom electronics analyze an electrical copy. The left and right channels are isolated with 47 k Ω resistors, summed, AC-coupled, biased around 1.65 V, protected, buffered by an MCP6002, and low-pass filtered before reaching an ESP32-S3 ADC. This direct-input approach is more repeatable than a room microphone because microphone placement, room acoustics, and unrelated conversations do not affect the input waveform.

The ESP32-S3 extracts three musical features. A fundamental-frequency estimator classifies clear single notes from C4 through B4 and selects a fixed RGBW color. An adaptive onset detector and inter-beat history estimate tempo and create beat-synchronized motion commands. RMS or smoothed amplitude scales brightness. Four independent LED PWM outputs command constant-current RGBW channels, while two standard servo PWM outputs move a pan-tilt light head. The current hardware architecture uses a 9 V input, separate 3.3 V and 5 V buck rails, a 25 mm square Cree RGBW head board, USB-C for firmware/debugging, and two Hitec HS-311 servos.

1.2 Visual Aid

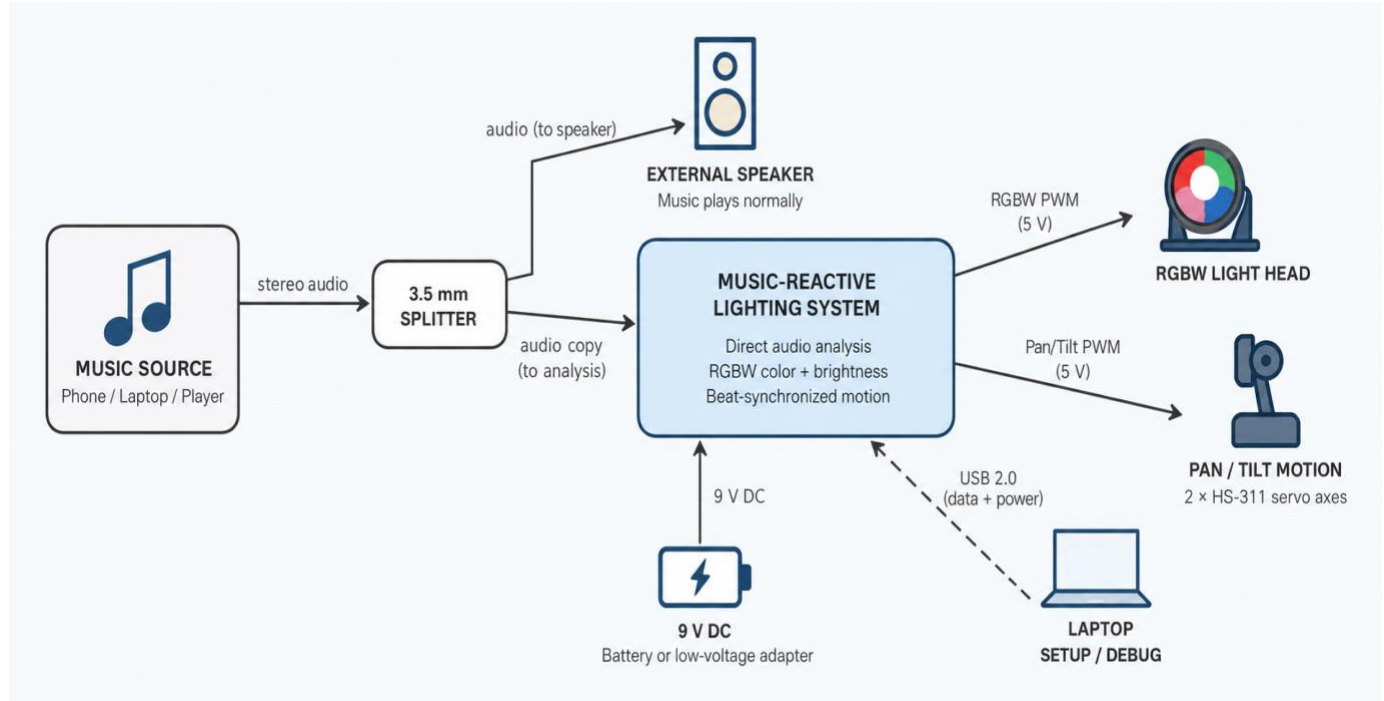


Figure 1. System context. The source audio is split to the speaker and the lighting system; the device generates synchronized RGBW output and pan-tilt motion.

The visual aid shows how the system is used rather than how its internal circuitry is divided. The speaker, music source, low-voltage power source, and setup laptop are external to the project. The laptop is only required for firmware loading and debugging; normal music-reactive operation is local to the embedded system.

1.3 High-Level Requirements

- The completed system shall correctly classify the pitch class and command the assigned RGBW color in at least 63 of 70 isolated-note trials, consisting of 10 trials each for C4, D4, E4, F4, G4, A4, and B4, using 0.5 V_{rms} synthesized tones applied directly to the 3.5 mm input.
- The completed system shall estimate reference tempos from 60 to 180 BPM with an absolute error no greater than 5 BPM after no more than 5 seconds of rhythmic input, and the measured input-onset-to-LED-PWM update latency shall not exceed 100 ms.
- The RGBW subsystem shall independently control four channels with at least 8-bit brightness resolution and a PWM carrier of at least 1 kHz; each channel shall regulate to 90-110 mA at full command, and the RGBW head shall remain at or below 60 °C during a 15-minute all-channels-on test at 25 °C $\pm$ 3 °C ambient.
- The pan and tilt axes shall each provide at least 60° of usable commandable motion and shall settle to within $\pm$ 5° of a commanded position within 0.50 s for a 45° step while the associated 5 V servo rail remains between 4.75 V and 5.25 V.

2. Design

2.1 Block Diagram and System Architecture

System Block Diagram

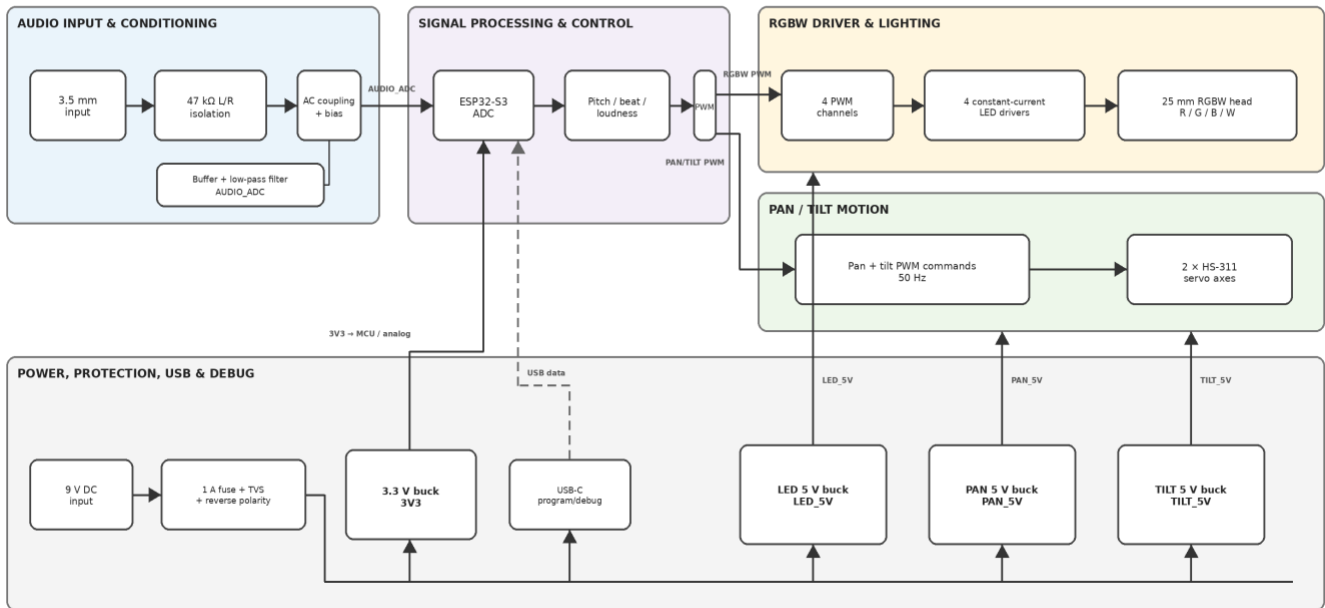


Figure 2. System block diagram. The design separates audio acquisition, embedded processing, RGBW output, motion, and power so each subsystem can be assembled and verified independently.

The design is divided into five functional subsystems: Audio Input and Conditioning, Signal Processing and Control, RGBW Driver and Lighting, Pan/Tilt Motion, and Power/Protection/USB. The main analog interface is the AUDIO_ADC signal into the ESP32-S3. The principal control interfaces are four LED duty-cycle outputs and two servo PWM outputs. Separate 5 V rails for the LED, pan servo, and tilt servo reduce coupling of transient actuator current into the ADC and 3.3 V logic rail. The USB-C path is a setup and debug interface and is not required during autonomous operation.

2.2 Physical Design

Physical Design and Mechanical Interfaces

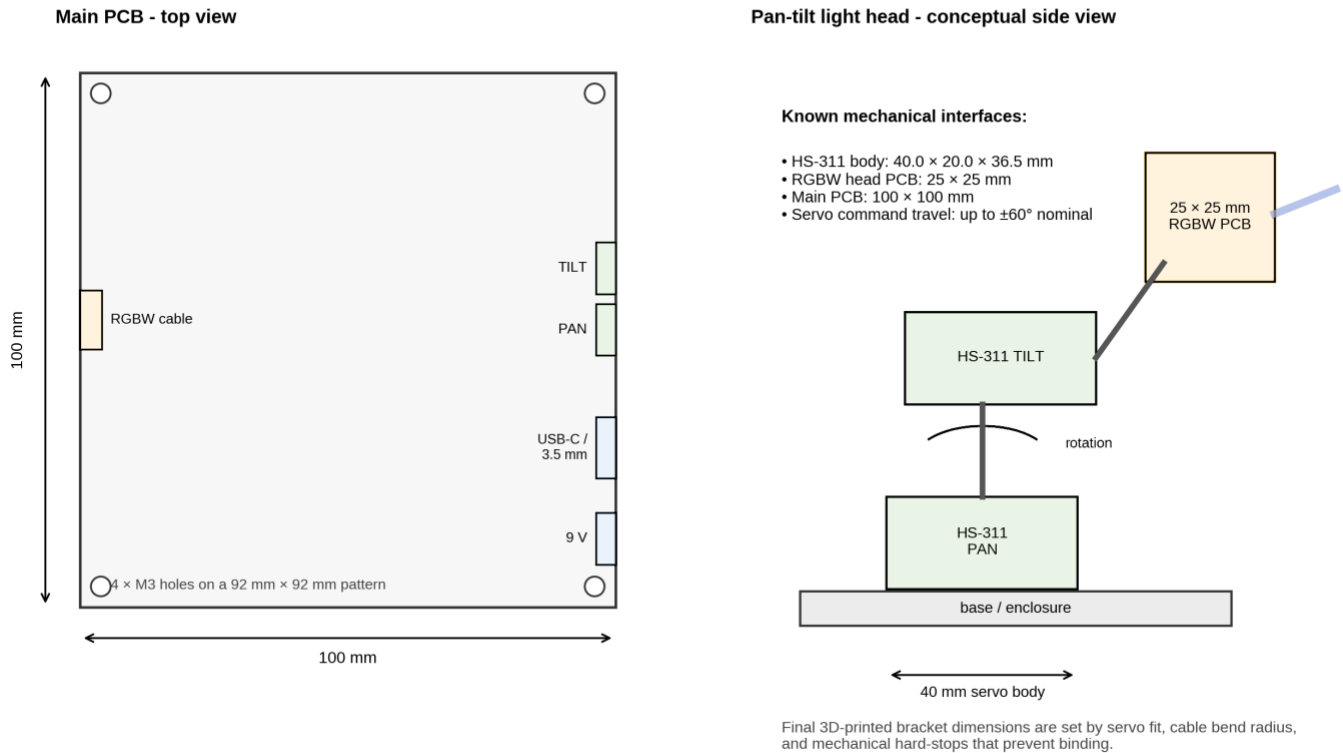


Figure 3. Physical design. The main PCB is 100 mm by 100 mm with four M3 mounting holes; the separate RGBW head PCB is 25 mm square and is carried by a two-axis servo assembly.

The main PCB outline in the current CAD is 100 mm by 100 mm. Four M3 mounting holes are located on a 92 mm by 92 mm pattern, leaving approximately 4 mm from each board edge to the hole center. The power, USB-C/audio, and pan/tilt connectors are placed along the right side of the board, while the five-wire RGBW head connector is on the left side. The separate light-head PCB is 25 mm by 25 mm and carries the 4-in-1 RGBW emitter. This separation keeps the optical head small and allows it to move without rotating the main electronics.

Two Hitec HS-311 servos form the motion assembly. Each servo body is approximately 40.0 mm × 20.0 mm × 36.5 mm and accepts 4.8-6.0 V PWM control. The pan servo is fixed to the base or enclosure; the tilt servo is supported by the pan axis; and the 25 mm RGBW board mounts to the tilt horn/bracket. Mechanical hard-stops will be placed inside the servo command range so the bracket cannot bind. The five-conductor LED cable and three-conductor servo cables require enough slack and bend radius for the full motion range.

Design Item	Implementation / Target
Main PCB	100 mm × 100 mm, 2-layer prototype, four M3 holes on 92 mm × 92 mm pattern.
RGBW head PCB	25 mm × 25 mm, separate moving board connected to main PCB by a five-wire harness.
Pan/Tilt actuators	2 × Hitec HS-311, 40.0 mm × 20.0 mm × 36.5 mm each, nominal ±60° servo command travel.
External interfaces	9 V DC input, 3.5 mm stereo input, USB-C programming/debug, RGBW head cable, pan servo, tilt servo.
Fabrication release gate	PCB fabrication is released only after electrical-rule checks and design-rule checks have no unresolved errors that affect manufacturability or safety.

2.3 Audio Input and Conditioning Subsystem

Design Item	Implementation / Target
Purpose	Convert stereo line-level audio into a protected, biased, band-limited ADC signal.
Input	3.5 mm stereo source through J2; intended verification range 0-2.0 Vrms per channel.
Channel isolation	R1 = 47 kΩ and R2 = 47 kΩ prevent direct shorting of left and right outputs.
Bias and buffer	R3 = R4 = 100 kΩ create VBIAS_RAW near 1.65 V; MCP6002 buffers the bias and audio signal.
Protection	BAT54S clamp networks limit abnormal input/ADC excursions; series resistance limits clamp current.
Filter	R6 = 3.3 kΩ, C5 = 10 nF first-order low-pass, nominal $f_c = 4.82$ kHz.
Output	AUDIO_ADC centered near 1.65 V, sampled by the ESP32-S3 at 16 ksample/s or greater.

The two source channels are never connected directly together. Separate 47 kΩ resistors form a passive resistive sum, maintaining high input impedance while creating a mono analysis signal. The summed AC component is coupled into a bias network so the bipolar audio waveform can be digitized by a single-supply ADC. The current schematic uses equal 100 kΩ bias-divider resistors, so the nominal reference is one-half of the 3.3 V logic rail, or 1.65 V. One MCP6002 section buffers the reference and the second section buffers the audio path. The op-amp is appropriate because it operates from a low-voltage single supply and has rail-to-rail output capability [5].

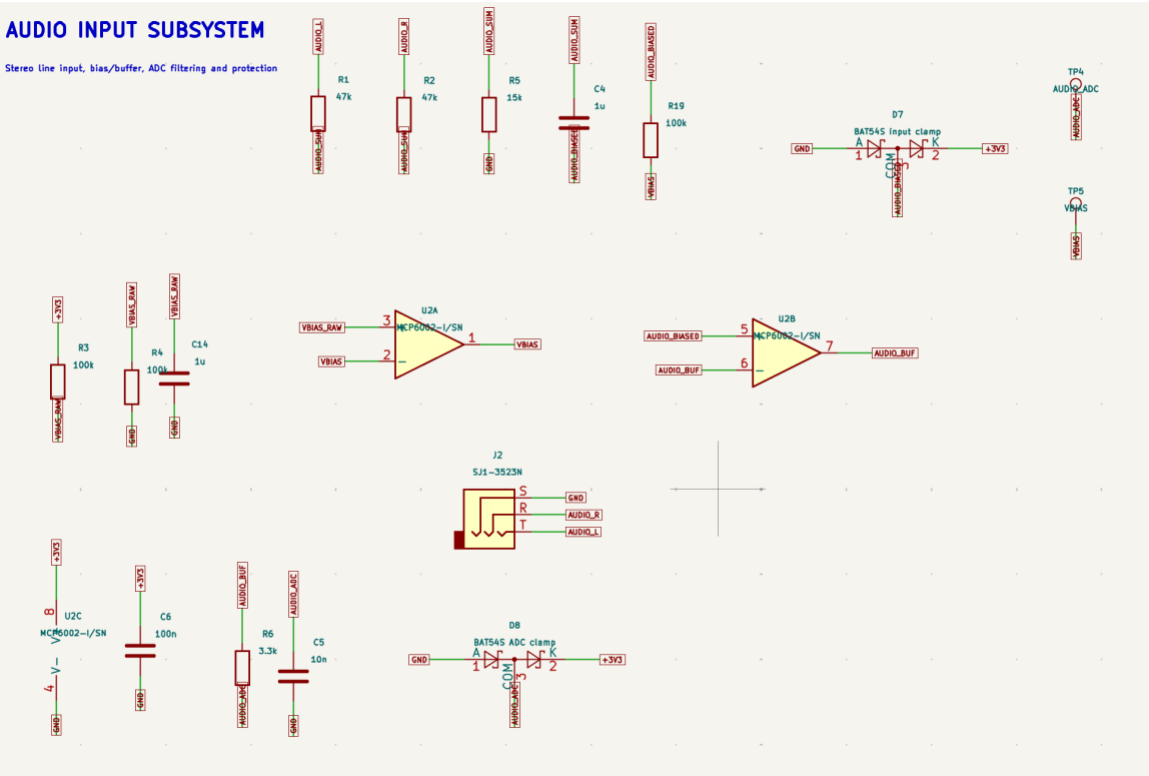


Figure 4A. Audio Input Subsystem Schematic

R6 and C5 form the final analog low-pass stage. With $R = 3.3 \text{ k}\Omega$ and $C = 10 \text{ nF}$, $f_c = 1/(2\pi RC) = 4.82 \text{ kHz}$. This passes the C4-B4 pitch range with negligible attenuation and reduces higher-frequency content before the 16 ksample/s ADC. Because it is only a first-order filter, it is treated as a noise-limiting front end rather than a steep anti-alias filter. Pitch verification is intentionally performed with controlled single-tone inputs below 500 Hz.

This subsystem supports High-Level Requirements 1 and 2. If the input clips, shifts outside the ADC range, or couples switching noise into the sampled waveform, pitch accuracy and beat timing will fail even if the digital algorithms are correct. Test points for AUDIO_ADC and VBIAS provide direct access during bring-up and verification.

Audio Subsystem Requirements and Verifications

Requirement	Verification Procedure and Pass Criterion
With no audio applied, VBIAS and AUDIO_ADC DC level shall be 1.65 V $\pm$ 0.10 V.	Power the board from 9.0 V. Connect a DMM to TP5 (VBIAS) and TP4 (AUDIO_ADC) relative to TP3 (GND). Record both voltages after 30 s. Pass if each is 1.55-1.75 V.
For equal left/right sine inputs from 0.5 to 2.0 Vrms, the conditioned ADC waveform shall remain between 0.30 V and 3.00 V.	Use a dual-channel function generator or split mono source to drive J2. Observe TP4 with an oscilloscope at 0.5, 1.0, 1.5, and 2.0 Vrms, 440 Hz. Record Vmin and Vmax. Pass if all waveforms remain inside 0.30-3.00 V without flat-topping.
The effective input impedance seen by either source channel shall be at least 40 k Ω in the 100 Hz-1 kHz band.	With power off, measure the resistance from each signal contact of J2 toward the summing network and confirm the 47 k Ω isolation resistor is present. With a source resistance method at 1 kHz, confirm effective loading remains $\geq$ 40 k Ω .
The analog low-pass cutoff shall be 4.0-6.0 kHz.	Drive J2 with a constant-amplitude sine sweep from 500 Hz to 8 kHz. Measure TP4 amplitude with an oscilloscope. Determine the -3 dB frequency relative to 500 Hz. Pass if the measured cutoff is within 4.0-6.0 kHz.
The ESP32-S3 shall acquire AUDIO_ADC at $\geq$ 16 ksample/s with no dropped-frame rate above 0.1% during a 60 s capture.	Run firmware that timestamps completed ADC frames and reports missed samples over USB serial. Apply a 1 kHz tone for 60 s. Pass if the measured rate is $\geq$ 16,000 samples/s and dropped samples are $\leq$ 0.1%.

2.4 Signal Processing and Control Subsystem

Design Item	Implementation / Target
Controller	ESP32-S3-WROOM-1-N8R8.
Audio sample rate	16 ksample/s minimum.
Pitch path	64 ms classifying frame, DC removal, autocorrelation-based fundamental estimate, nearest natural note C4-B4.
Beat path	Short-time energy envelope, adaptive threshold, minimum refractory interval, rolling inter-beat history.
Loudness path	RMS or smoothed amplitude mapped monotonically to 0-100% output brightness.
LED control	Four hardware PWM channels, target 2 kHz and at least 8-bit resolution.
Servo control	Two 50 Hz PWM outputs, nominal 900-2100 μ s command window, motion rate limited in firmware.
Debug	Native USB path plus 3.3 V UART/debug test points on the PCB.

Figure 4. Signal processing flow. Pitch, onset timing, and loudness are derived in parallel and combined by the output mapper.

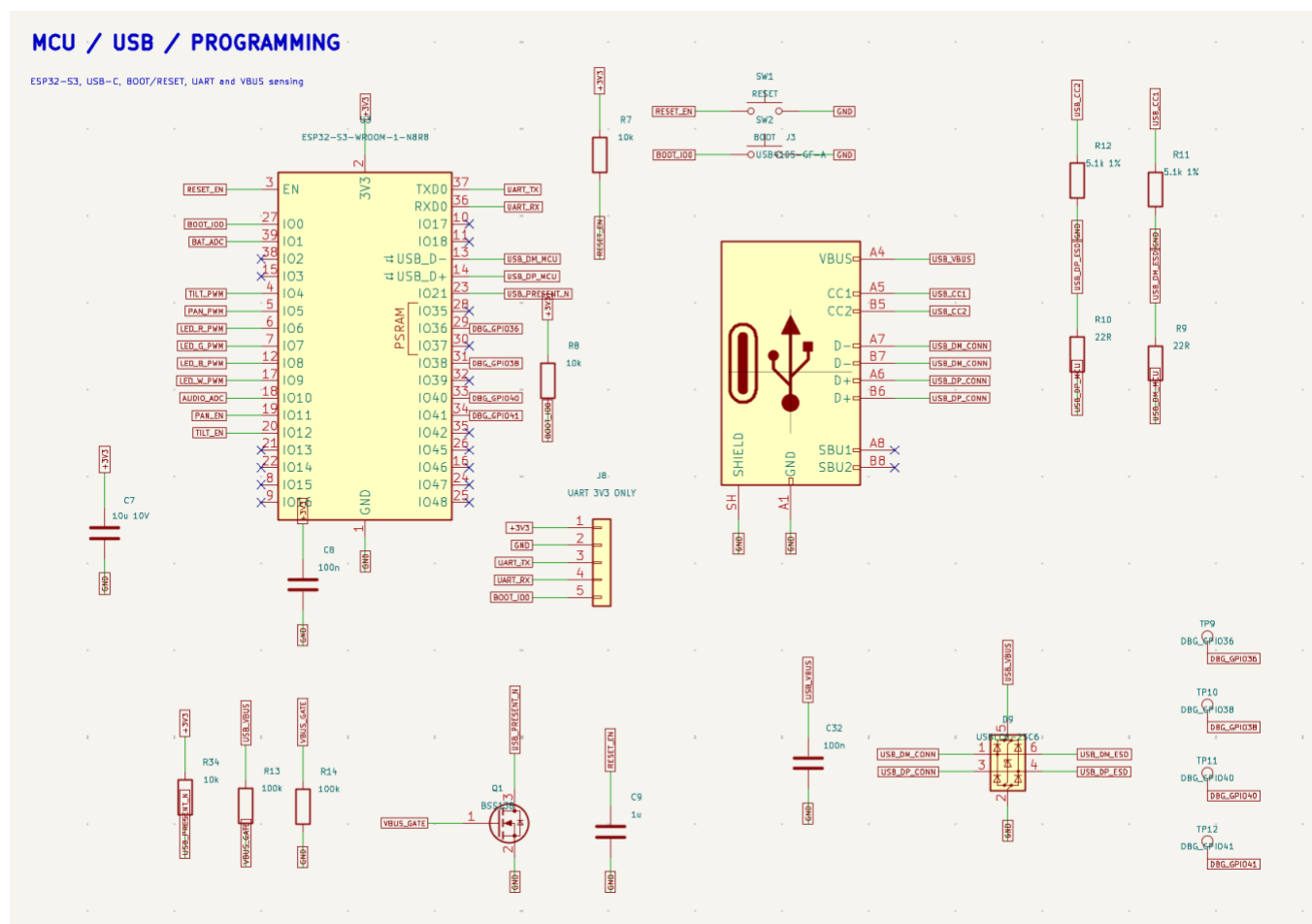


Figure 5A. MCU and USB-C Subsystem Schematic

The digital pipeline is designed around bounded latency. A 16 ksamples/s rate yields 64 ms for a 1024-sample pitch frame. The firmware removes the 1.65 V DC bias and runs an autocorrelation search over lags corresponding to approximately 220-550 Hz. The strongest valid correlation peak is refined by local interpolation and converted to frequency. During the defined verification trials, the measured frequency is assigned to the nearest of the seven natural-note targets C4, D4, E4, F4, G4, A4, and B4. Overlapped updates allow a new classification more frequently than once per 64 ms frame.

Beat detection uses a shorter energy path. Squared or absolute sample energy is accumulated over short windows, compared with a moving baseline, and accepted as an onset only when the threshold is crossed after a refractory interval. Inter-onset intervals are retained in a rolling history; outliers are rejected and the median or trimmed mean is converted to BPM. This prevents a single false trigger from producing a large tempo jump. The loudness path uses RMS or an exponential envelope and scales the selected color vector. The white channel is available for broadband accents, but it is held at zero during the isolated-note color verification so pitch-to-color results remain unambiguous.

Pitch	Reference Frequency	Verification Color Command (R,G,B,W)
C4	261.63 Hz	(255, 0, 0, 0) - red
D4	293.66 Hz	(255, 96, 0, 0) - amber
E4	329.63 Hz	(255, 200, 0, 0) - yellow
F4	349.23 Hz	(0, 255, 0, 0) - green
G4	392.00 Hz	(0, 220, 255, 0) - cyan
A4	440.00 Hz	(0, 0, 255, 0) - blue
B4	493.88 Hz	(180, 0, 255, 0) - magenta

Table 1. Fixed pitch-to-color mapping used for repeatable verification. Overall brightness multiplies the RGB components without changing pitch class.

Beat-synchronized motion is intentionally rate-limited so the light head does not chatter. The output mapper changes the pan/tilt target on accepted beats or on a small beat-count pattern, interpolates between positions, and clamps commands inside the tested mechanical limits. The servo control frequency is independent of the LED PWM frequency.

Signal Processing and Control Requirements and Verifications

Requirement	Verification Procedure and Pass Criterion
Pitch-to-color accuracy shall be $\geq 90\%$ over the defined 70 isolated-note trials.	Generate 0.5 Vrms sine tones for C4, D4, E4, F4, G4, A4, and B4. Apply 10 trials per note through J2. Log detected pitch and RGBW command over USB serial. Pass if at least 63 of 70 trials select the correct pitch and Table 1 color.
Tempo estimate shall be within ± 5 BPM for 60, 90, 120, 150, and 180 BPM inputs after ≤ 5 s.	Feed reference click/beat tracks at each target tempo. Start from no-history state and record time to stable estimate plus reported BPM. Pass if every target reaches a value within ± 5 BPM within 5 s.
Input onset to LED PWM command latency shall be ≤ 100 ms.	Drive the audio input with a reference pulse or abrupt 1 kHz burst and monitor the corresponding LED PWM pin on a second oscilloscope channel. Measure at least 30 events. Pass if the worst measured delay is ≤ 100 ms.
LED PWM shall provide ≥ 8 -bit duty resolution at ≥ 1 kHz on four independent outputs.	Use a logic analyzer on all four LED PWM nets. Sweep each command from 0 to full scale while holding the other channels fixed. Pass if all channels operate ≥ 1 kHz and at least 256 distinct command levels are addressable without cross-coupling.
Brightness mapping shall be monotonic with input level over the verification range.	Apply a 440 Hz tone at 0.10, 0.20, 0.30, 0.40, and 0.50 Vrms. Record commanded duty cycle after settling. Pass if duty never decreases as input level increases and no step exceeds the allowed 0-100% bounds.

2.5 RGBW Driver and Lighting Subsystem

Design Item	Implementation / Target
Emitter	Cree CLQ6B-TKW family, 4-in-1 RGBW, separate die connections on a 25 mm $\times$ 25 mm head PCB.
Driver topology	Four independent constant-current sink channels controlled by LED_R_PWM, LED_G_PWM, LED_B_PWM, and LED_W_PWM.
Current setpoint	RSET = 4.99 k Ω , targeting approximately 100 mA per color channel in the current CAT4101 implementation.
Supply	Dedicated regulated LED_5V rail from an LMR50410 buck regulator.
Control	PWM dimming from ESP32-S3; target 2 kHz, requirement ≥ 1 kHz.
Harness	Five conductors between main PCB and moving RGBW head: common LED supply plus four controlled channel returns.
Availability risk	CAT4101TV-T75 is marked obsolete in the project procurement sheet; driver availability must be resolved before PCB fabrication while preserving the 100 mA/PWM requirements.

The selected Cree CLQ6B-TKW emitter is a compact 4-in-1 RGBW device with independent red, green, blue, and white die connections. The data sheet characterizes each color at 100 mA, which matches the present current target [8]. Four constant-current channels are used instead of current-limiting resistors so LED current is less sensitive to forward-voltage differences among colors. In the present schematic, a 4.99 k Ω RSET resistor is used for each CAT4101 channel; the CAT4101 data sheet lists 4.99 k Ω as the 100 mA setting [7].

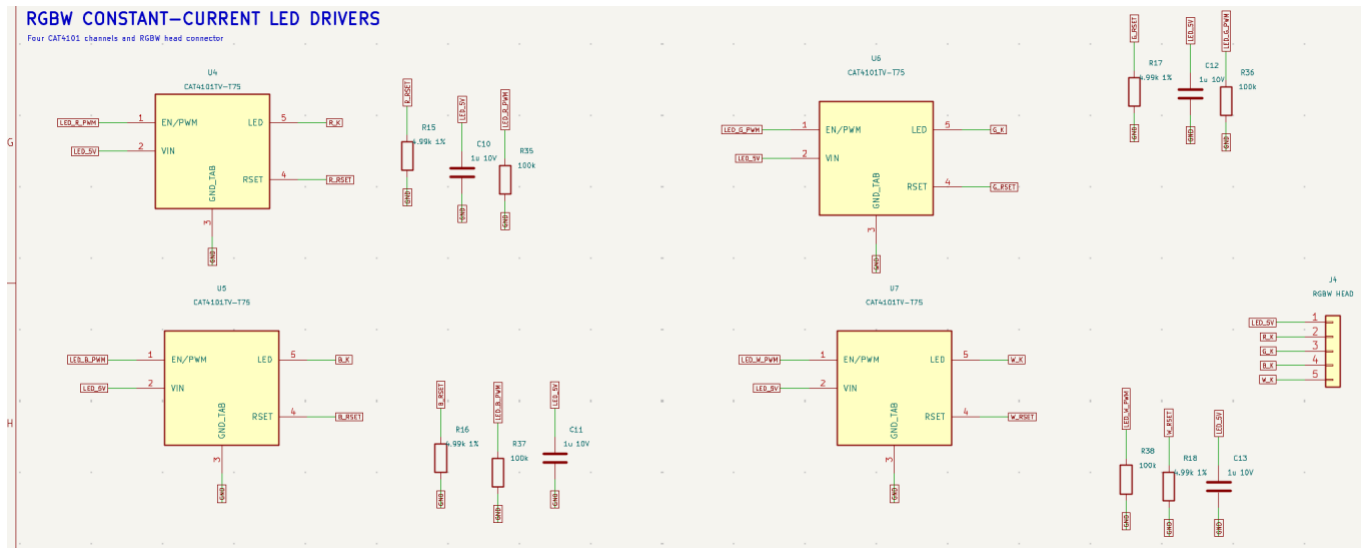


Figure 6A. RGBW Driver and Lighting Subsystem Schematic

The constant-current channels are powered from the LED_5V rail and accept independent PWM commands. For pitch trials, color selection is determined by the fixed mapping in Table 1; brightness is applied as a scalar to the channel duty cycles. The LED head is separated from the main PCB so only the small optical assembly moves. The short head cable must be routed so it cannot pull on the tilt axis or rub against a sharp bracket edge.

RGBW Driver and Lighting Requirements and Verifications

Requirement	Verification Procedure and Pass Criterion
Each color channel shall regulate 90-110 mA at full command with the selected 5 V LED supply.	Command one channel at 100% while the other three are off. Measure channel current with a DMM or current probe. Repeat for R, G, B, and W. Pass if each measured current is 90-110 mA.
Each channel shall respond independently to 0-100% PWM without uncontrolled flicker or cross-channel activation.	Use a logic analyzer on PWM and a current probe or photodiode on the LED output. Sweep one channel while others remain at 0%. Repeat for each color. Pass if only the commanded color changes and the response follows duty cycle.
LED PWM frequency shall be ≥ 1 kHz.	Measure each LED PWM signal with an oscilloscope or logic analyzer. Pass if all four carrier frequencies are ≥ 1 kHz over 0-100% duty commands.
The RGBW head shall remain ≤ 60 °C during a 15-minute all-channels-full thermal test at 25 °C ± 3 °C ambient.	Attach a thermocouple to the head PCB adjacent to the emitter. Command all four channels to maximum allowed current for 15 min. Log temperature once per minute. Pass if the maximum recorded temperature is ≤ 60 °C.
On MCU reset or loss of PWM drive, the LED channels shall default to off.	Operate all channels at visible brightness, then press RESET and separately force each PWM control low. Pass if the corresponding LEDs turn off without a sustained unintended output.

2.6 Pan/Tilt Motion Subsystem

Design Item	Implementation / Target
Actuators	2 $\times$ Hitec HS-311 standard analog servos.
Supply	Separate PAN_5V and TILT_5V rails, each generated by a 1 A LMR50410 buck regulator.
Servo operating range	4.8-6.0 V; current data sheet lists up to approximately 800 mA stall current at 6 V [9].
Command protocol	50 Hz PWM, nominal 1500 μ s center, approximately 900-2100 μ s usable command window.
Motion behavior	Beat-synchronized target changes with interpolation and software limits to prevent chatter or hard-stop loading.
Mechanical safety	Hard-stops and command clamps prevent bracket interference; cables are strain-relieved and kept outside moving pinch points.

The current design uses a dedicated regulator for each servo rather than powering both from a single rail. The HS-311 operating range is 4.8-6.0 V, its no-load current is roughly 160-180 mA, and its listed stall current reaches approximately 700-800 mA depending on supply voltage [9]. A 1 A rail therefore provides useful per-axis current margin, while 470 μ F local bulk capacitors on the servo rails reduce short transient dips. Separating the two servo supplies also prevents a single moving axis from directly disturbing the other servo or the LED rail.

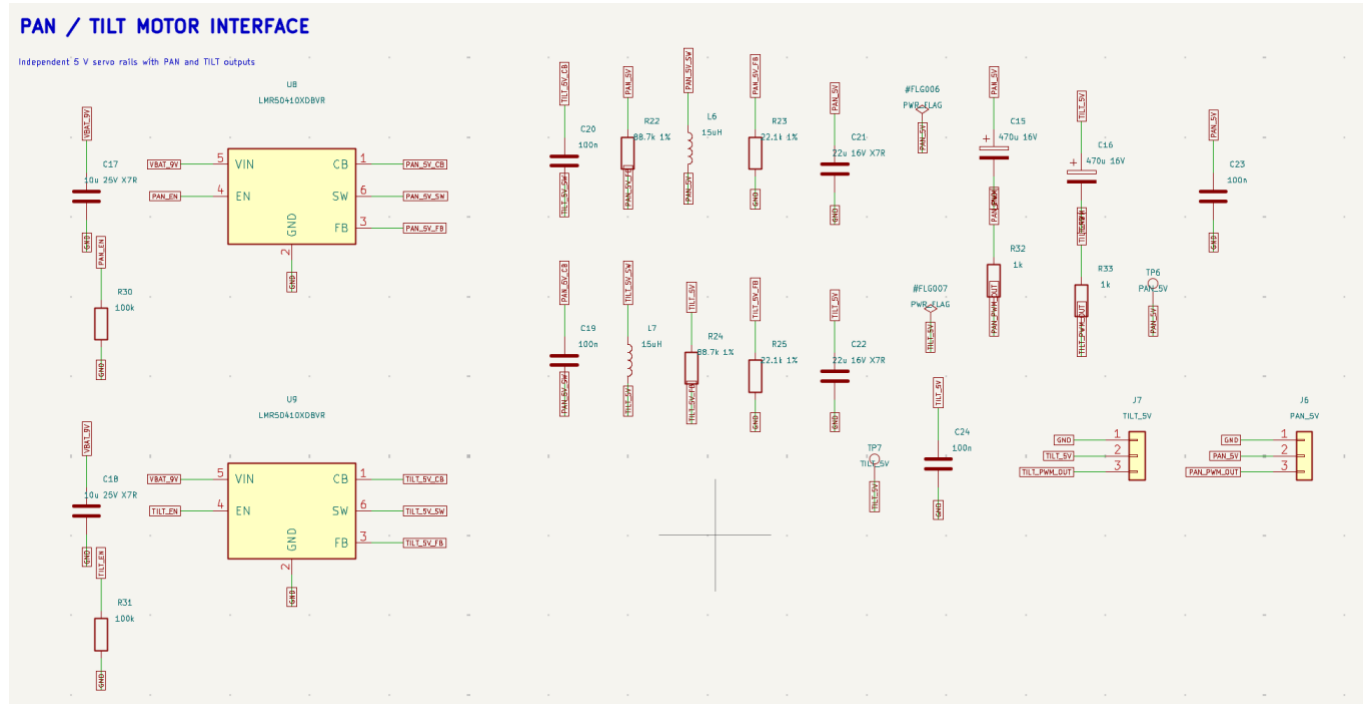


Figure 7A. Pan/Tilt Motion Subsystem Schematic

Servo positions are commanded at 50 Hz. Firmware clamps pulse width to the mechanically validated range and applies a slew limit when moving between targets. The intended musical behavior is not to chase every instantaneous sample. Instead, accepted beats advance or modify the pan/tilt target, and the servo trajectory is interpolated over a fraction of a second. This preserves a visible rhythmic response while avoiding mechanical chatter and excess current.

The motion subsystem contributes directly to High-Level Requirement 4 and indirectly to the visual quality of the system. Mechanical requirements are verified using angle markings or a digital angle gauge rather than relying on the nominal servo specification alone.

Pan/Tilt Motion Requirements and Verifications

Requirement	Verification Procedure and Pass Criterion
Each axis shall provide at least 60° of usable motion without binding or cable interference.	Mark the neutral orientation and command the tested minimum and maximum positions. Measure physical angle with a digital angle gauge or printed protractor. Pass if each axis covers $\geq 60^\circ$ total usable range and moves freely throughout.
For a 45° position step, each axis shall settle within $\pm 5^\circ$ of the target within 0.50 s.	Attach an angle gauge or record high-frame-rate video against a fixed protractor. Command a 45° step from rest and measure time until the axis remains within $\pm 5^\circ$ for at least 100 ms. Repeat five times per axis. Pass if all trials meet 0.50 s.
During commanded motion, PAN_5V and TILT_5V shall remain between 4.75 V and 5.25 V under normal non-stall operation.	Probe each servo rail with an oscilloscope using a short ground lead. Command repeated 45° moves while the LED subsystem is active. Pass if the rail stays within 4.75-5.25 V during the test.
Firmware shall not command the servo into a mechanical hard-stop.	Determine the first command value that approaches each physical stop, then set software limits at least 5° inside that position. Exercise all programmed motion patterns for 10 min. Pass if no impact, binding, sustained buzzing, or repeated high-current stall occurs.
A servo fault shall not reset the ESP32-S3 during normal verification.	While streaming debug output, repeatedly move one axis through the allowed range and briefly add moderate mechanical load without forcing a hard stall. Pass if the MCU does not reset and 3.3 V remains within its requirement.

2.7 Power and Debug Subsystem

Design Item	Implementation / Target
Primary input	9 V DC through J1; portable testing may use a 9 V battery and bench/demo operation may use a regulated low-voltage adapter.
Input protection	F1 1 A fast fuse, SS34 Schottky reverse-polarity element, SMBJ12A TVS, input bulk/ceramic capacitors.
Logic rail	LMR50410 buck, RFBT = 51.0 k Ω , RFBB = 22.1 k Ω , nominal 3.31 V, 10 μ H inductor.
LED rail	LMR50410 buck, RFBT = 88.7 k Ω , RFBB = 22.1 k Ω , nominal 5.01 V, 15 μ H inductor.
Pan/Tilt rails	Two additional LMR50410 5 V rails using the same 88.7 k Ω / 22.1 k Ω divider target; local bulk capacitance supports servo transients.
Battery monitor	100 k Ω / 27 k Ω divider scales the 9 V input to a safe BAT_ADC level for optional firmware monitoring.
USB	GCT USB4105-GF-A receptacle, 5.1 k Ω CC resistors, 22 Ω USB data series resistors, USBLC6-2SC6 ESD protection.
Debug access	UART header plus test points for VBAT_9V, +3V3, GND, AUDIO_ADC, VBIAS, PAN_5V, TILT_5V, LED_5V, and selected GPIO signals.

All custom electronics operate from low-voltage DC. The LMR50410 is a 4-36 V, 1 A synchronous buck converter with a 1.0 V feedback reference [6]. For the 3.3 V rail, $V_{OUT} = 1.0 \times (1 + 51.0/22.1) = 3.31$ V. For each 5 V rail, $V_{OUT} = 1.0 \times (1 + 88.7/22.1) = 5.01$ V. Using separate converters prevents servo and LED load transients from sharing the same regulated node as the ESP32-S3 and analog front end.

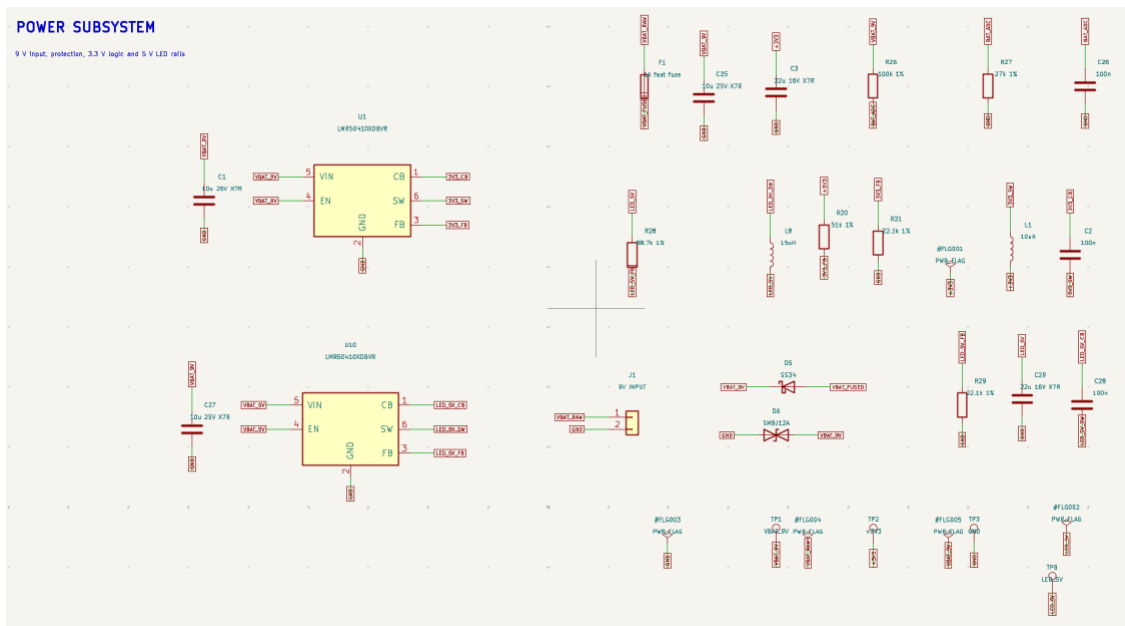


Figure 8. Power and Debug Subsystem Schematic

The 9 V input is protected before it fans out to the buck converters. The fuse limits sustained fault current, the Schottky element addresses reverse-polarity connection, and the TVS suppresses short overvoltage transients. The custom board contains no mains-voltage conversion. The USB-C connector is used only for native USB programming/debug. CC pull-down resistors identify the board as a USB device, 22 Ω series resistors damp the D+/D- path, and a USBLC6 device provides ESD protection.

The input fuse is intentionally part of the system-level current budget. Normal servo motion is far below the two-axis simultaneous stall condition, but the design must avoid deliberately driving both axes against hard-stops while the LED

load is at maximum. Firmware motion limits, mechanical stops, and separate bulk capacitance reduce the probability of a current surge that would collapse the source or open the input fuse.

Power, Protection, USB, and Debug Requirements and Verifications

Requirement	Verification Procedure and Pass Criterion
The +3V3 rail shall remain between 3.20 V and 3.40 V during normal integrated operation.	Probe TP2 with a DMM and oscilloscope. Run audio processing, LED effects, and repeated servo moves for 5 min. Pass if the rail remains 3.20-3.40 V with no MCU brownout.
Each 5 V rail shall remain between 4.75 V and 5.25 V over its intended load range.	Use an electronic load or the actual subsystem. Sweep LED_5V from 0-0.5 A and each servo rail from idle to representative motion current while measuring voltage. Pass if each stays 4.75-5.25 V.
Input overcurrent and reverse-polarity protection shall prevent unsafe board operation.	With a current-limited bench supply, verify correct operation at +9 V. Then power off and perform continuity/polarity checks across the Schottky path before applying a reversed source at a safe current limit. Confirm no reverse-powered downstream rail. Verify the installed fuse rating is 1 A.
USB programming/debug shall enumerate and transfer data without resets during a 5-minute serial session.	Connect a laptop by USB-C, flash firmware, and stream status data for 5 min while the board is externally powered. Pass if enumeration is stable, no unexpected resets occur, and no ESD/protection component overheats.
All named power and analog test points shall be accessible after assembly.	After PCB assembly, identify TP1-TP12 using silkscreen and a board drawing. Pass if a standard scope probe or DMM lead can contact each intended test point without shorting adjacent pads.

2.8 PCB Layout and Integration Considerations

The main board is a 2-layer, 100 mm × 100 mm PCB. The layout should treat the audio input and VBIAS area as a quiet analog region, keep the high-current servo and LED regulator loops compact, and route switching-current returns away from the audio summing node. Ground pours and stitching vias provide a low-impedance return while test points support subsystem-by-subsystem bring-up. The ESP32-S3 antenna keepout and USB differential-pair routing must remain clear of noisy switch nodes and large copper interruptions.

Power traces should be wider than low-current logic traces with a width of 1mm and 0.5mm if it is near the ESP-32. Logic traces should have a width of at least 0.25mm. The design includes reset and boot switches, a UART header, and dedicated debug GPIO test points so firmware problems can be separated from analog, power, and USB problems during assembly.

Before fabrication, the PCB release checklist is: resolve the LED-driver procurement choice, update the schematic and footprint if the selected driver changes, run ERC, run DRC to zero unresolved fabrication errors, verify every schematic symbol is linked to the intended footprint, confirm board labels/team number/revision/date, verify ground planes and stitching vias, inspect power-trace widths and connector pinouts, and generate/inspect Gerbers and drill files. This release gate is part of the schedule in Section 3.2.

2.9 Tolerance Analysis

The most critical analog interface is the audio-conditioning chain because a clipped or badly biased waveform can cause both the pitch and beat requirements to fail. The current design combines equal left/right inputs through 47 kΩ resistors and biases the resulting AC signal using a 15 kΩ path to the buffered 1.65 V reference. The analysis below uses 1% resistor tolerance for the summing/bias resistors, a 3.3 V rail range of 3.2-3.4 V, and a 10% tolerance for the 10 nF filter capacitor. These assumptions are intentionally more conservative than nominal values.

For equal left and right signals, the two 47 kΩ source resistors appear as 23.5 kΩ in parallel. The nominal AC gain to the summing node is therefore $A = 15/(23.5 + 15) = 0.3896$. With 1% resistors, the maximum gain occurs when the 15 kΩ resistor is high and the 47 kΩ inputs are low: $A_{max} = 15.15/(23.265 + 15.15) = 0.3944$.

The 100 kΩ/100 kΩ bias divider nominally creates $V_{BIAS} = 1.65$ V. Including ±1% resistor tolerance and the specified 3.2-3.4 V logic-rail requirement gives a worst-case bias range of approximately 1.584-1.717 V. A 2.0 V_{rms} sine wave has a 2.828 V peak. At $A_{max} = 0.3944$, the largest AC deviation is about 1.115 V peak. Combining this with worst-case bias gives an estimated waveform range of 0.469-2.832 V. This remains inside the 0.30-3.00 V verification window and below the ESP32-S3 high-attenuation effective upper range used for this design [4].

Parameter	Nominal	Worst Low	Worst High
VBIAS	1.650 V	1.584 V	1.717 V

Parameter	Nominal	Worst Low	Worst High
Common-stereo gain	0.3896	≈ 0.385	0.3944
2.0 Vrms conditioned minimum	≈ 0.548 V	0.469 V	-
2.0 Vrms conditioned maximum	≈ 2.752 V	-	2.832 V
R6/C5 filter cutoff	4.82 kHz	4.34 kHz	5.41 kHz

Table 2. Worst-case audio-front-end tolerance summary.

The R6/C5 low-pass cutoff is $f_c = 1/(2\pi RC)$. For $R = 3.3 \text{ k}\Omega \pm 1\%$ and $C = 10 \text{ nF} \pm 10\%$, the cutoff varies from approximately 4.34 kHz to 5.41 kHz, remaining inside the 4.0-6.0 kHz subsystem requirement. Figure 5 shows the corresponding first-order response. At the highest verification pitch, $B4 \approx 493.9 \text{ Hz}$, attenuation is negligible for all tolerance cases.

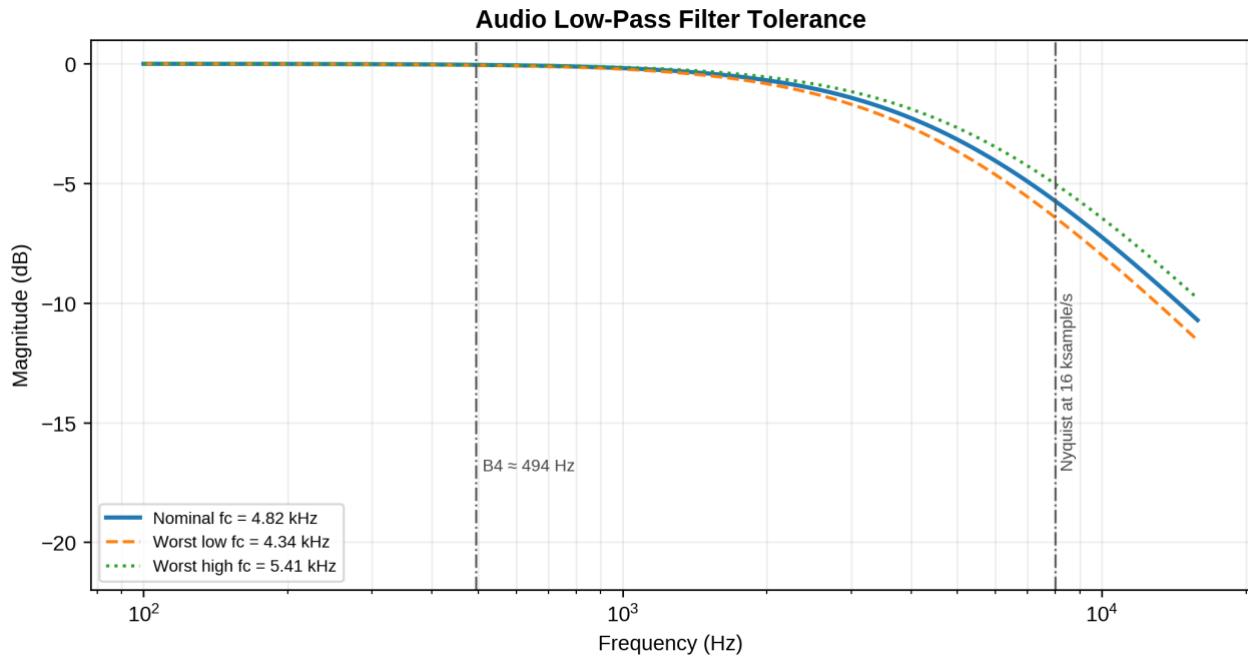


Figure 5. Low-pass filter magnitude for nominal and worst-case RC tolerances.

The tolerance analysis shows that the current input scaling leaves useful ADC headroom at the maximum defined line-level test input while the filter tolerance stays inside the required band. The remaining practical risks are source levels above the 2.0 Vrms verification range and noise coupled from switching regulators. Input clamps, layout separation, direct test points, and the subsystem verification procedures address those risks.

3. Cost and Schedule

3.1 Cost Analysis

Labor is estimated using the UIUC Electrical Engineering 2024-2025 reported average starting salary of \$87,429 per year [18]. Assuming 2,080 work hours per year gives an equivalent base rate of \$42.03/hour. Following the ECE 445 cost convention, labor cost is estimated as hourly rate $\times 2.5 \times$ project hours. A planning estimate of 120 hours per student is used for the semester.

Team Member	Base Rate	Multiplier	Hours	Estimated Labor
Disha Ghosh	\$42.03/hr	2.5	120	\$12,609.95
Annie Mak	\$42.03/hr	2.5	120	\$12,609.95
Total labor				\$25,219.90

Table 3. Labor cost estimate.

The parts table below is based on the uploaded project procurement workbook. Known-price components total \$102.14. Several small passives/protection parts and the final LED-driver choice are not yet priced. To avoid presenting an incomplete grand total as exact, the budget includes a clearly labeled \$30 provisional allowance for unpriced electronics and a \$15 allowance for shipping/consumables.

Part / Service	Manufacturer / Part No.	Qty	Known Cost	Notes
9 V alkaline batteries	Energizer EN22 / UIUC stock	2	\$6.08	Testing spares
9 V battery clip	UIUC stock	1	\$0.43	Input wiring
9 V PCB battery holder	UIUC stock	1	\$2.00	Optional mechanical retention
Pan servo	Hitec HS-311	1	\$27.02	Pan axis
Tilt servo	Hitec HS-311	1	\$27.02	Tilt axis
9 V / 1 A wall adapter	PS-912 / UIUC stock	1	\$17.95	Bench/demo fallback; use only within tested current envelope
ESP32-S3 module	ESP32-S3-WROOM-1-N8R8	1	\$6.32	Main controller
Dual op-amp	MCP6002-I/SN	1	\$0.41	Audio conditioning
USB-C receptacle	GCT USB4105-GF-A	1	\$0.80	J3
3.5 mm stereo jack	Same Sky SJ1-3523N	1	\$1.12	J2
Buck regulator ICs	TI LMR50410 family	4	\$8.20	3.3 V + three 5 V rails; verify exact order code
Power inductors	Bourns SRN6045, 10/15 μ H	4	\$1.72	1 $\times$ 10 μ H + 3 $\times$ 15 μ H; exact values not found in self-service inventory, so purchased cost retained
RGBW emitter	Cree CLQ6B-TKW series	1	\$0.67	Exact bin TBD
Precision LED RSET resistors	4.99 k Ω 1% 0805	4	\$0.40	4.99 k Ω 1% not found in self-service list; purchased estimate retained
PCB fabrication	PCBWay (ECE 445 course order)	1	\$0.00	Course-order 2-layer PCB; no project charge
Unpriced electronics allowance	LED-driver replacement, ESD/protection, passives, 22.1 k Ω & 88.7 k Ω buck feedback resistors	1	\$30.00	Budgetary estimate; includes exact buck feedback resistor values not found in self-service drawers
Shipping and consumables allowance	Shipping, wire, hardware, solder/printing	1	\$15.00	Budgetary estimate
Drawer resistors	ECE self-service drawers	24	\$0.00	Schematic values available by nominal value: 22 Ω $\times$ 2, 1 k Ω $\times$ 2, 3.3 k Ω $\times$ 1, 5.1 k Ω $\times$ 2, 10 k Ω $\times$ 3, 15 k Ω $\times$ 1, 27 k Ω $\times$ 1, 47 k Ω $\times$ 2, 51 k Ω $\times$ 1, 100 k Ω $\times$ 12. Verify 1% tolerance where required.

Part / Service	Manufacturer / Part No.	Qty	Known Cost	Notes
Capacitors	ECE self-service drawers	30	\$0.00	Schematic: 10 nF ×1, 100 nF ×10, 1 μF ×7, 10 μF ×6, 22 μF ×4, 470 μF ×2. Drawer inventory includes these nominal capacitances; use voltage/package ratings appropriate to schematic.

Table 4. Prototype parts and services cost estimate.

Cost Category	Amount
Known-price project subtotal from parts plan	\$100.14
Provisional unpriced electronics allowance	\$30.00
Shipping/consumables allowance	\$15.00
Budgeted prototype materials	\$145.14
Estimated labor	\$25,219.90
Grand project cost estimate	\$25,365.04

Table 5. Grand cost estimate. Labor dominates the academic project cost; physical prototype spending is budgeted at approximately \$147 before final receipts.

3.2 Schedule

Week	Team Task	Disha	Annie
Sep 21-27	Finalize architecture and schematic interfaces	Audio/control review, test plan	Power/LED/motion review, mechanical interfaces
Sep 28-Oct 4	Design document and PCB release cleanup	DSP design, R&V definitions	PCB routing, connector/mechanical checks
Oct 5-11	Resolve LED driver, zero ERC/DRC, order/fabricate PCB	Firmware framework, ADC capture	Finalize BOM, fabrication files, pan-tilt bracket
Oct 12-18	Prepare bring-up fixtures and firmware	Pitch/beat prototype on bench waveforms	Servo motion code and mechanical assembly
Oct 19-25	PCB assembly and power bring-up	3.3 V/USB/ESP32 bring-up	9 V protection and three 5 V rails
Oct 26-Nov 1	Analog + LED subsystem bring-up	Audio bias/filter/ADC validation	RGBW driver/head current validation
Nov 2-8	Motion integration	Output mapper and beat commands	Pan/tilt range, limits, cable management
Nov 9-15	Full system integration	Pitch/tempo tuning and logging	Lighting/motion integration and power-noise debug
Nov 16-22	Quantitative verification round 1	Pitch, tempo, latency tests	Current, rail, motion, thermal tests
Nov 23-29	Fixes and regression verification	Algorithm fixes and rerun	Hardware/mechanical fixes and rerun
Nov 30-Dec 6	Demo hardening and documentation	Final firmware freeze, plots/results	Mechanical freeze, final BOM/photos
Dec 7-final demo	Final verification, demonstration, report	Demo operation and software evidence	Demo setup and hardware evidence

Table 6. Weekly construction, integration, and verification schedule.

4. Societal Impact, Engineering Standards, Ethics, and Safety Considerations

4.1 Societal, Economic, Environmental, Cultural, and Global Impact

The project makes responsive lighting more accessible for student events, small venues, home listening spaces, and interactive installations without requiring a dedicated lighting operator or an expensive show-control system. The design performs all analysis locally and uses a direct electrical input instead of an always-listening room microphone, which

reduces incidental capture of nearby conversations. This also makes behavior more repeatable across rooms and reduces dependence on network connectivity or cloud services.

Economically, the system is built from a small custom PCB, commodity embedded components, two standard servos, and a compact RGBW emitter. Environmentally, the modular architecture allows the main PCB, servos, power source, and RGBW head to be replaced independently rather than discarding the entire device after one component failure. The algorithm responds to pitch, onset timing, and amplitude rather than a song database, so it does not depend on a particular genre, language, or cultural music catalog. A 3.5 mm source adapter may be required for modern phones without an analog audio connector.

The principal public-welfare concern is visual stimulation. High-contrast flashes can cause discomfort and may trigger photosensitive responses in susceptible viewers. The system therefore uses a high LED PWM carrier and limits deliberate scene-level beat flashes to the low beat-rate range used by the project. A steady or low-motion operating mode can be used during extended testing or for users who prefer reduced visual motion.

4.2 Engineering Standards and Professional Guidance

Standard / Guidance	Relevance	Design Response
IEEE 1789-2015	Recommended practices for LED current modulation and potential viewer health effects.	Use a PWM carrier ≥ 1 kHz, avoid deliberate rapid high-contrast flashing, and verify no unintended low-frequency flicker.
IEC 62471 / IEC 62471-7:2023	Photobiological safety framework for lamps and visible light sources.	Do not stare directly into the emitter during bench tests; control exposure, orientation, and diffuser use as appropriate.
UL/CSA 62368-1	Hazard-based safety framework for AV/ICT equipment and external power conversion.	Keep mains conversion outside the custom PCB; use only approved low-voltage adapters during demonstration.
USB 2.0 / USB Type-C device conventions	Electrical interface used for programming/debug.	Use CC pull-downs, D+/D- series resistors, ESD protection, and controlled routing to the ESP32-S3.
ECE 445 R&V guidelines	Subsystem requirements must be quantitative and each requirement must have a repeatable verification procedure.	Every subsystem in this document includes measurable thresholds, equipment, procedures, and explicit pass criteria.
ECE 445 laboratory safety rules	Course rules govern laboratory work, training, and risk mitigation.	Complete required training, do not work alone in the lab, and use current-limited supplies, eye protection, and safe rework procedures.

Table 7. Standards and guidance applied to the project.

4.3 IEEE/ACM Ethics and Course Ethics

The IEEE Code of Ethics emphasizes public safety, honest technical claims, competence, disclosure of limitations, and correction of errors [14]. The ACM Code similarly emphasizes contributing to human well-being, avoiding harm, and being honest and trustworthy [15]. These principles directly affect how the project is designed and demonstrated. Verification results will be reported as measured, failed tests will not be hidden, and the system will not be described as recognizing arbitrary polyphonic music if the demonstrated requirement only covers isolated notes and rhythm features.

The direct-audio architecture also limits privacy risk. The system does not need an always-on microphone, does not store room conversations, and does not need to upload audio to an external service. Debug logs should contain extracted engineering values rather than recorded user audio unless a short waveform capture is intentionally taken for testing. Any stored test audio should be generated or used with permission.

4.4 Electrical, Optical, Thermal, Mechanical, and Laboratory Safety

Hazard	Risk	Mitigation Procedure	Verification / Evidence
Electrical short or reverse input	Overheating, damaged board, battery/adaptor stress	Use 1 A fuse, reverse-polarity element, TVS, current-limited bench supply for bring-up, inspect polarity before power.	Power protection R&V; thermal inspection during first power-up.
Servo stall / pinch point	High current, hot servo, finger/cable pinch	Software angle limits, mechanical hard-stops, no hands in moving bracket during automated test, power off before mechanical adjustment.	10-minute motion pattern without stall/binding; rail-voltage measurement.
High-brightness LED exposure	Eye discomfort or optical hazard	Do not stare into emitter; aim away from eye level during bench work; use diffuser or reduced duty for close inspection.	Document test orientation and maximum allowed duty/current.
Photosensitive flicker	Discomfort or seizure risk for susceptible viewers	LED PWM ≥ 1 kHz, avoid deliberate rapid high-contrast flash effects, provide steady/reduced-motion mode.	Measure carrier frequency and review effect timing before demo.

Hazard	Risk	Mitigation Procedure	Verification / Evidence
Hot components / soldering	Burns and fumes	Use fume extraction/ventilation, eye protection, insulated tools, allow power components to cool before handling.	Follow ECE 445 lab safety procedures and required training.
Sharp leads / rotating harness	Cuts, snagging, conductor fatigue	Trim leads, use strain relief, route cables away from servo horns, cover exposed sharp edges.	Mechanical inspection through full pan/tilt range.
Battery use	Leakage or overheating under excessive load	Use fresh commercial 9 V alkaline batteries only within tested load; do not charge primary cells; remove battery when not in use.	Record source current during battery-mode test and inspect for heating.

Table 8. Project safety hazards and mitigation procedures.

References

- [1] University of Illinois ECE 445, "Design Document" sample and format guidance. https://courses.grainger.illinois.edu/ece445/guidelines/design_document.pdf
- [2] University of Illinois ECE 445, "Requirements and Verification." <https://courses.grainger.illinois.edu/ece445/guidelines/requirements-and-verification.asp>
- [3] University of Illinois ECE 445, "Tolerance Analysis Guide." <https://courses.grainger.illinois.edu/ece445/documents/tolerance-analysis-guide.pdf>
- [4] Espressif Systems, "ESP32-S3 Series Datasheet," ADC and device characteristics. https://documentation.espressif.com/esp32_s3_datasheet_en.pdf
- [5] Microchip Technology, MCP6002 dual rail-to-rail operational amplifier product data. <https://www.microchip.com/en-us/product/MCP6002>
- [6] Texas Instruments, "LMR50410 SIMPLE SWITCHER 4-V to 36-V, 1-A Buck Converter." <https://www.ti.com/product/LMR50410>
- [7] onsemi, "CAT4101 1 A Constant-Current LED Driver with PWM Dimming." <https://www.onsemi.com/pdf/datasheet/cat4101-d.pdf>
- [8] Cree LED, "CLQ6B-TKW: PLCC8 4-in-1 RGBW SMD LEDs." <https://assets.cree-led.com/a/ds/h/HB-CLQ6B-TKW.pdf>
- [9] Hitec Commercial Solutions, "HS-311 Standard Voltage Servo Actuator." <https://www.hiteccs.com/actuators/product-details/HS-311>
- [10] GCT, USB4105-GF-A USB Type-C receptacle product information. <https://gct.co/connector/usb4105>
- [11] Epilepsy Foundation, "Photosensitivity and Seizures." <https://www.epilepsy.com/what-is-epilepsy/seizure-triggers/photosensitivity>
- [12] IEC, IEC 62471 / IEC 62471-7, photobiological safety of lamps and visible light sources. <https://webstore.iec.ch/en/publication/68810>
- [13] IEEE Standards Association, IEEE 1789-2015, LED modulation and viewer health guidance. <https://standards.ieee.org/ieee/1789/4479/>
- [14] IEEE, "Code of Ethics." <https://www.ieee.org/about/corporate/governance/p7-8.html>
- [15] Association for Computing Machinery, "ACM Code of Ethics and Professional Conduct." <https://www.acm.org/about-acm/acm-code-of-ethics-and-professional-conduct>
- [16] UL Solutions, UL/CSA 62368-1 hazard-based product safety guidance. <https://www.ul.com/insights/navigating-requirements-ulcsa-62368-1-4th-edition>
- [17] University of Illinois ECE 445, "Safety." <https://courses.grainger.illinois.edu/ece445/guidelines/safety.asp>
- [18] University of Illinois ECE, "Salary Averages," AY 2024-25. <https://ece.illinois.edu/admissions/why-ece/salary-averages>
- [19] DigiKey and UIUC ECE Supply Center pricing sources as listed in the project parts workbook. <https://my.ece.illinois.edu/storeroom/catalog.asp>
- [20] PCBWay, prototype PCB fabrication pricing reference. <https://www.pcbway.com/>

Appendix A. Consolidated Verification Equipment

Equipment	Used For	Key Measurements
2+ channel oscilloscope	Audio, rail transients, latency, PWM	Vmin/Vmax, ripple, onset-to-PWM delay, servo/LED pulse timing
Logic analyzer	Digital PWM and firmware timing	PWM frequency, duty changes, independent channel behavior
DMM / current meter	DC rails and LED current	3.3 V/5 V rails, channel current, resistance checks
Function generator / audio source	Repeatable analog verification	0.5-2.0 Vrms tones, click tracks, swept sine
Thermocouple / contact temperature probe	Thermal verification	RGBW head temperature over 15 minutes
Digital angle gauge / protractor	Pan/tilt verification	Usable range, position error, step response
USB laptop / serial logger	Firmware verification	Pitch, BPM, ADC rate, dropped frames, resets

Table A.1. Equipment required for subsystem and system-level verification.