

Posture & Neck Strain Monitor for Long Study Sessions

ECE 445 Design Document

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1 Introduction

1.1 Problem and Solution

Problem. Long study or work sessions make it easy to slip into poor posture without noticing until neck or back pain has set in. Research on the cervical spine shows the load on the neck grows sharply as the head tilts forward and down [1]. Existing solutions are poorly suited to everyday use: desk-mounted cameras are expensive and raise privacy concerns, back braces are bulky and uncomfortable for long wear, and app-based trackers typically require a subscription and constant phone interaction. A single orientation sensor cannot directly measure head-to-torso tilt; two sensors provide this relative measurement, while a dwell timer distinguishes brief glances from sustained tilt. Commercial single-sensor wearables such as the UPRIGHT GO 2 [15] attach to the upper back and vibrate when the trunk slouches, but they sense trunk motion at one point, do not measure head orientation, and are paired with a smartphone app. Our design differs in two ways: a second sensor at the head makes the relative head-to-torso angle observable, and all processing and feedback happen on the device with no phone or subscription. We need a small, low-cost, standalone device that reliably monitors posture and neck strain and nudges the wearer when they slouch, without requiring a phone or subscription.

Solution. We propose a two-IMU wearable. One IMU is clipped to the glasses (head orientation) and one to the collar or shirt (torso orientation). The device estimates each sensor's tilt relative to gravity and subtracts them to obtain the relative head-to-torso angle, which estimates relative neck tilt. Using the relative angle (rather than either sensor's absolute orientation) allows common body tilt to be distinguished from relative neck tilt: whole-body movement, such as leaning back in a chair, moves both sensors together and cancels out. During setup the wearer calibrates a "neutral" baseline while seated normally. The device then monitors deviation from that baseline in real time, and if the deviation is held past a threshold for 10 seconds it vibrates (and optionally lights an LED) to prompt a correction. No phone, camera, or subscription is needed. As an extra goal, a BLE module logs posture data to a companion phone app.

1.2 Visual Aid

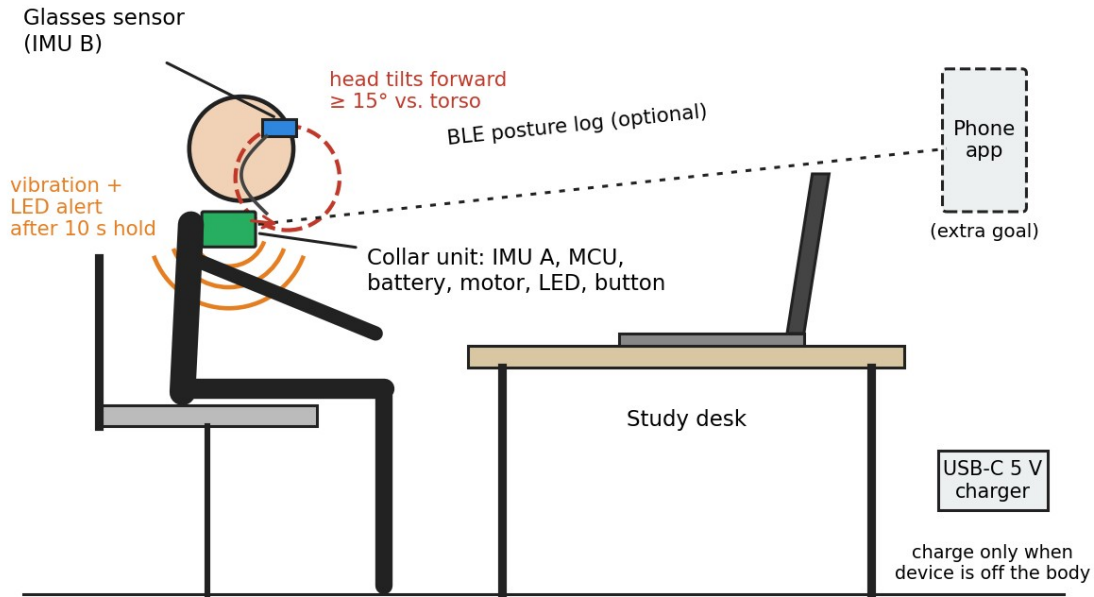


Figure 1: The device in use. A seated wearer carries a glasses-mounted head sensor and a collar-mounted main unit joined by a thin cable; a forward head tilt held for 10 s produces a vibration and LED alert. Solid lines are the core standalone system; the dotted line to a phone is the optional BLE extra goal.

1.3 High-Level Requirements

- The device must detect a sustained change of at least 15° in relative head-to-torso pitch or roll from the calibrated baseline, held for 10 seconds, and alert within 1 second after the hold completes. Detection must exceed 90% in each of three 20-trial groups: head-only tilt, torso-only tilt, and combined head/torso tilt. Brief 5-second tilts, pure yaw, and common head/torso tilt with unchanged relative orientation must not alert. These are distinct negative-control trials, not exceptions to the sustained relative-angle requirement.
- The device must run continuously for at least 8 hours of active monitoring on a single charge, verified by bench testing.
- The fully assembled device (both IMU boards, main PCB, battery, vibration motor, enclosures) must weigh no more than 25 g, and the enclosures must be no larger than $4\text{ cm} \times 3\text{ cm} \times 1.5\text{ cm}$ (main) and $1.5\text{ cm} \times 1\text{ cm} \times 0.5\text{ cm}$ (glasses sensor), measured on the assembled hardware.
- The alert must be reliably noticed: at least 8 of 10 test users must notice it within 3 seconds of triggering.

2 Design

2.1 Block Diagram

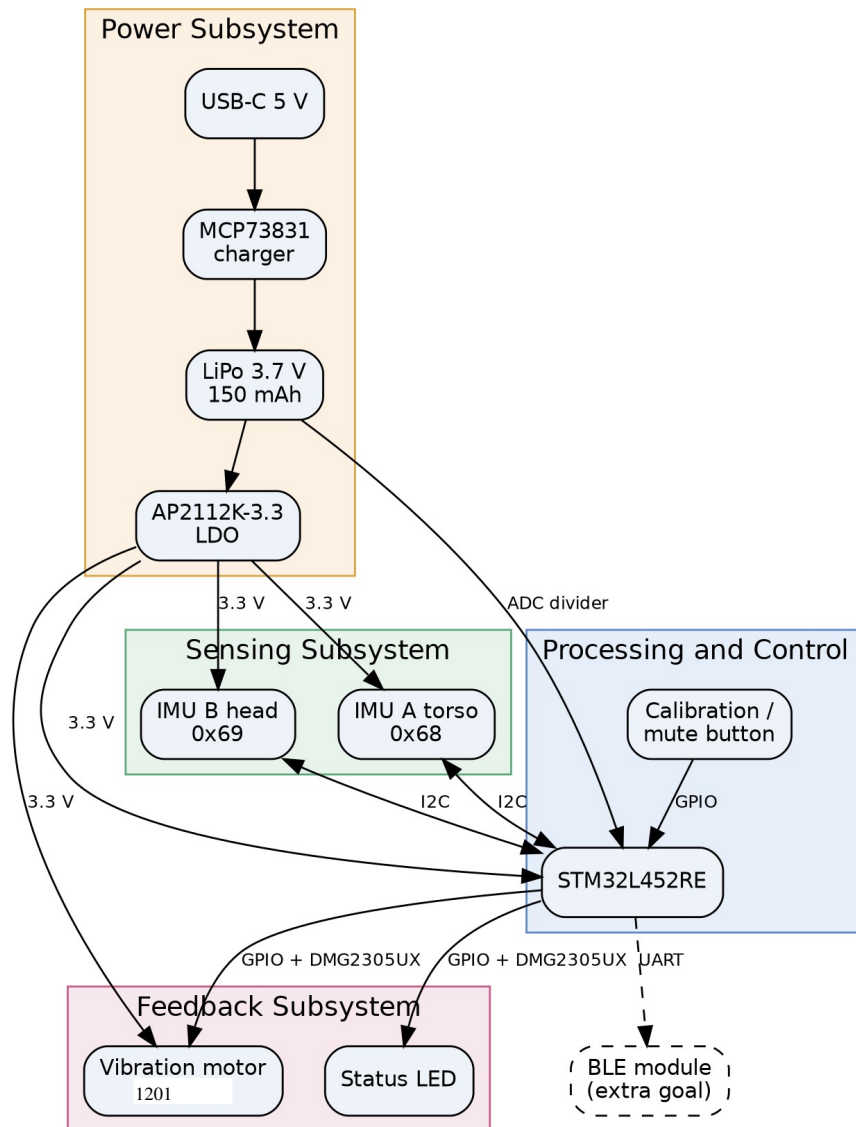


Figure 2: System block diagram. The 3.7 V battery label is nominal; active monitoring uses the planned loaded range 3.65–4.2 V with a 3.75 V warning and 3.65 V firmware cutoff.

The **Sensing Subsystem** captures raw acceleration and angular rate at the head and torso. The **Processing and Control Subsystem** (an STM32L452RE) reads both IMUs over one I2C bus, fuses accelerometer and gyro data into a tilt estimate per sensor, computes the relative angle, compares it to the stored baseline, times how long the wearer is out of range, and triggers alerts. The **Feedback Subsystem** delivers a discreet (vibration) and noticeable (LED) alert. The **Power Subsystem** charges the LiPo cell over USB-C and provides a clean 3.3 V rail to everything. The **Wireless Subsystem** is an optional extra goal.

2.2 Physical Design

The device has two physical parts joined by a thin cable:

- **Main assembly (collar clip):** main PCB ($\sim 36 \times 26$ mm), LiPo battery stacked beneath the PCB, vibration motor, LED, button, USB-C port, and IMU A, all in a 3D-printed enclosure of $40 \times 30 \times 15$ mm. Stack-up estimate: PCB 1.0 mm + tallest component (LQFP-64 MCU) 1.6 mm + battery ~ 5.5 mm + 2×1.2 mm walls ≈ 10.5 mm, leaving margin below 15 mm.
- **Glasses sensor board:** a tiny PCB ($\sim 12 \times 8$ mm) carrying IMU B ($2.5 \times 3.0 \times 0.76$ mm LGA), a 100 nF bypass capacitor, and a 4-pin connector (the I2C pull-ups are on the main board), in a $15 \times 10 \times 5$ mm enclosure that clips to the temple arm of the glasses. A breakaway (friction-fit) connector is used near the collar so that a snag releases the cable rather than pulling on the wearer.
- Axis convention: align both IMUs with +X forward and +Z upward in neutral posture. Record a sensor-to-body alignment transform during setup before comparing pitch and roll; baseline subtraction alone does not correct rotated axes. Mechanically constrain each clip against rotation. The observable is relative orientation, not neck translation, force, pain, or every form of torso slouching.

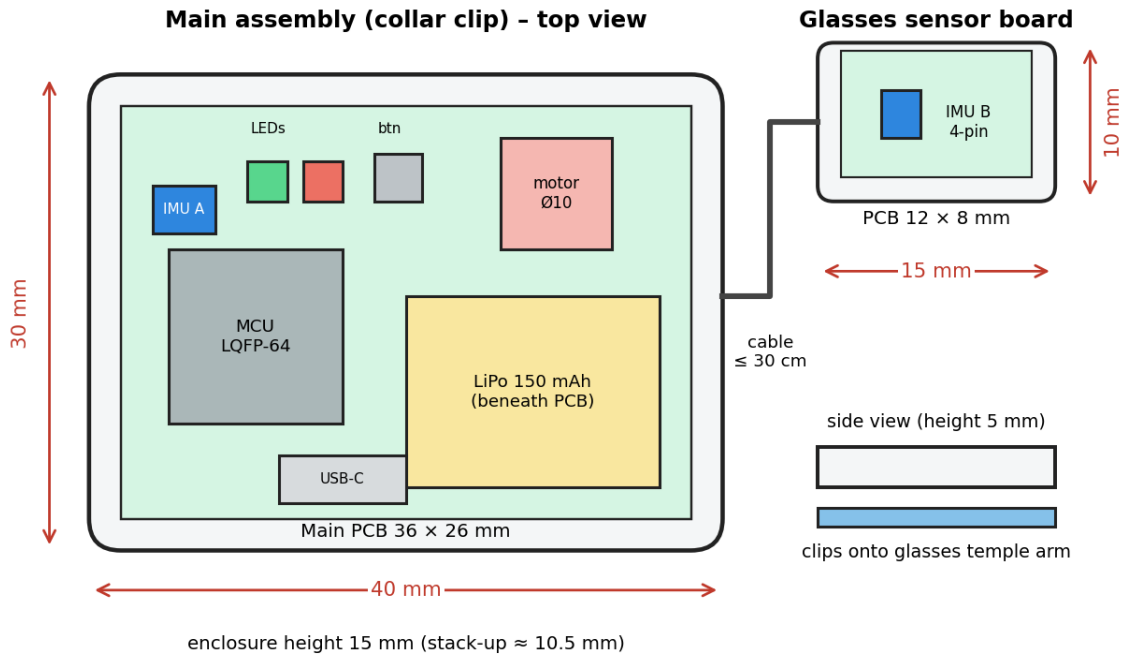


Figure 3: Physical design (dimensions in mm). Left: main collar assembly, top view with the stacked LiPo beneath the PCB. Right: glasses sensor board and its enclosure on the temple arm, joined to the main assembly by a cable of at most 30 cm.

Table 1 gives the estimated weight budget; each value is verified by weighing the assembled hardware against the 25 g limit of HLR 3.

Table 1: Estimated weight budget

Item	Estimated mass (g)
150 mAh LiPo	4.65 [11]
Main PCB with components	4.0
Glasses sensor PCB	0.3
Vibration motor	1.0
Cable and connectors	1.5
Enclosures (main 5.0 + sensor 0.7)	5.7
Total	≈17.2 (limit 25; other masses estimated)

2.3 Sensing Subsystem

Role in the high-level requirements. The relative head-to-torso angle is the quantity that all of High-Level Requirement 1 depends on. This subsystem provides it with enough accuracy and update rate to resolve a 15° change.

Design.

- Two **ICM-42670-P** 6-axis IMUs (TDK InvenSense) on one I2C bus. The AD0 pin sets the 7-bit address: **AD0 = GND** → **0x68** (torso IMU, on the main PCB), **AD0 = 3.3 V** → **0x69** (head IMU, on the glasses board, tied high on that board).
- Configuration: accelerometer ±2 g (best resolution for tilt), gyroscope ±500 dps (covers fast head movements), output data rate 100 Hz, on-chip low-pass filter ≈ 40 Hz. Operating in low-noise mode.
- **I2C interface:** 400 kHz Fast Mode, 3.3 V, 2.2 kΩ pull-ups on the main board. The cable to the glasses is ≤ 30 cm of 30 AWG wire (3.3 V, GND, SDA, SCL).
- **Bus timing check.** With an assumed total bus capacitance of ~65 pF (cable ≈ 30 pF, two IMU pins ≈ 20 pF, MCU pin and traces ≈ 15 pF), rise time $t_r \approx 0.8473 \times R \times C = 0.8473 \times 2.2 \text{ k}\Omega \times 65 \text{ pF} \approx \mathbf{121 \text{ ns}}$, well below the 300 ns Fast Mode maximum [7]. Pull-up sink current at 3.3 V is $3.3 \text{ V} / 2.2 \text{ k}\Omega = 1.5 \text{ mA}$, below the 3 mA I2C limit. (4)
- **Data volume:** reading 12 bytes of accel and gyro data per IMU is about 17 bytes including addressing, i.e., roughly 0.4 ms per IMU at 400 kHz, so about 0.8 ms of every 10 ms sample period.

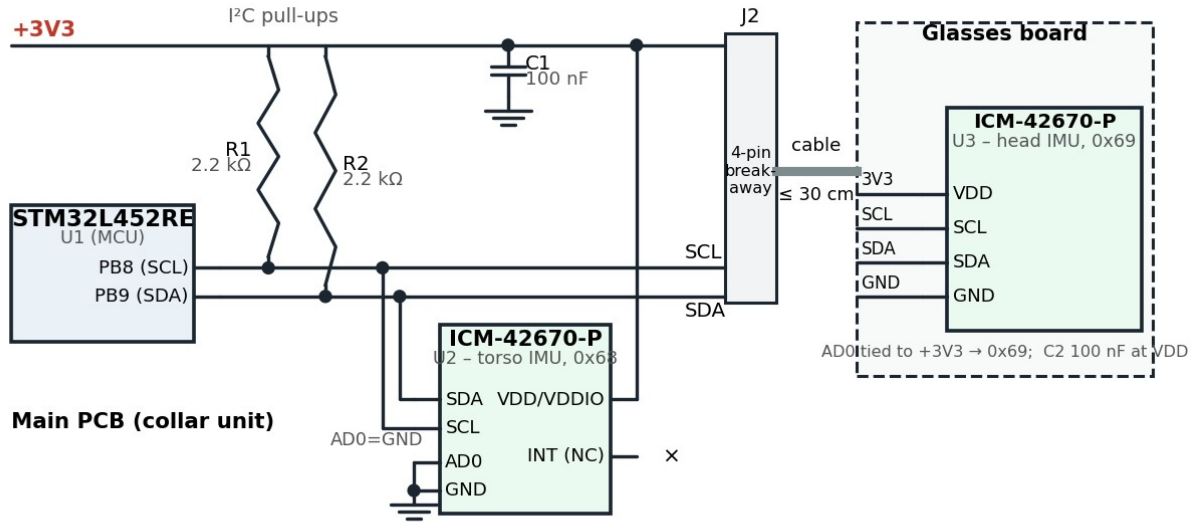


Figure 4: Sensing subsystem schematic. Both IMUs share one I²C bus with 2.2 kΩ pull-ups on the main PCB; address-select pin AD0 is tied to GND on the torso IMU (0x68) and to +3V3 on the glasses board (0x69).

Requirements and Verification (following the ECE 445 R&V guidance [2]; see Table 2).

Table 2: Sensing subsystem requirements and verification

Requirement	Verification
The student-designed I ² C bus (2.2 kΩ pull-ups, ≤ 30 cm cable, AD0 address straps) must enumerate exactly two devices at 0x68 and 0x69, each returning the datasheet WHO_AM_I value [3], with SDA/SCL rise time < 300 ns (design value ≈ 121 ns) and zero NACK/timeout errors over 20 min.	Run an I ² C address scan from the MCU and print results over UART; confirm exactly two devices and matching WHO_AM_I values. Probe SDA/SCL on an oscilloscope with the 30 cm cable attached and confirm rise time < 300 ns. Log I ² C error counters for 20 minutes and confirm zero errors.
The student-written sampling firmware must read both IMUs every 10 ms ± 1 ms (100 Hz) with timing jitter < 1 ms.	Toggle a GPIO on each completed read cycle; measure period on an oscilloscope over 60 s. Confirm 10 ms ± 1 ms.
Each IMU's tilt output (gravity-vector computation plus alignment transform) must be within ±2° of a reference angle at 0°, 15° and 30° in pitch and roll.	Mount each IMU on an angled jig (protractor or 3D-printed wedges) at 0°, 15°, and 30° in pitch and roll. Record the computed tilt over 10 s per angle; confirm mean error ≤ 2°.

2.4 Processing and Control Subsystem

Role in the high-level requirements. This subsystem turns raw IMU data into the alert decision (HLR 1) and determines how much power the device consumes (HLR 2).

Hardware. STM32L452RE [6] (Cortex-M4F with FPU, STM32L4 low-power family) powered at 3.3 V, running from the internal oscillator at 16 MHz. A single tactile push button on a GPIO with external interrupt, an ADC channel monitoring the battery through a 2×470 kΩ divider (≈ 4.5 μA), and an SWD header for programming. *Pin map:* I2C1 SCL/SDA on PB8/PB9, button on PC13 (EXTI), motor gate on PA6, green/red LED gates on PA5/PA4, battery ADC on PA0, SWD on PA13/PA14.

Algorithm.

1. *Tilt from gravity.* For each IMU, accelerometer pitch $\theta = \text{atan2}(-a_x, \sqrt{a_y^2 + a_z^2})$ and roll $\phi = \text{atan2}(a_y, a_z)$. Rotation about the vertical axis (yaw) does not change the gravity vector, so turning the head or torso left/right is ignored by design. (1)
2. *Complementary filter.* $\theta_k = \alpha \cdot (\theta_{k-1} + \omega \cdot \Delta t) + (1 - \alpha) \cdot \theta_{\text{acc}}$, with $\Delta t = 10$ ms and a time constant of $\tau = 2$ s ($\alpha = \tau / (\tau + \Delta t) \approx 0.995$). The gyro tracks fast motion; the accelerometer slowly removes gyro drift. [10] is background on attitude filtering; the scalar filter specified here is a simplified design choice, not an implementation of that paper's SO(3) algorithm. The accelerometer correction is frozen when $||a| - 1 \text{ g}| > 0.05 \text{ g}$, so that dynamic acceleration (e.g., a quick head turn) does not corrupt the estimate. (2)
3. *Relative angle.* $\Delta\theta = (\theta_{\text{head}} - \theta_{\text{torso}}) - \text{baseline}_{\theta}$ and $\Delta\phi = (\phi_{\text{head}} - \phi_{\text{torso}}) - \text{baseline}_{\phi}$. The strain metric is $S = \max(|\Delta\theta|, |\Delta\phi|)$. (3)
4. *Dwell timer with hysteresis.* Start the timer when $S \geq 12^\circ$. Count only consecutive samples with $S \geq 12^\circ$; any sample below 12° resets the pre-alert timer. Enter the alert state after 10 seconds. Once alerting, use $S < 10^\circ$ to release the alert, providing hysteresis without allowing time below the trigger threshold to accumulate. The 3° difference between the 15° physical target and the 12° measured trigger is an engineering margin, justified by the error budget in Section 2.8. Values from 10° to 15° form a transition region; an exact physical boundary is not claimed.
5. *Calibration and mute.* A **long press** (≥ 2 s) starts calibration: the wearer sits upright and still, the MCU averages 3 s (300 samples) of θ and ϕ for each IMU plus gyro bias, and writes the baseline to flash so it survives power-off. A **short press** mutes alerts for 30 minutes (press again to unmute); a press during an active alert silences it.

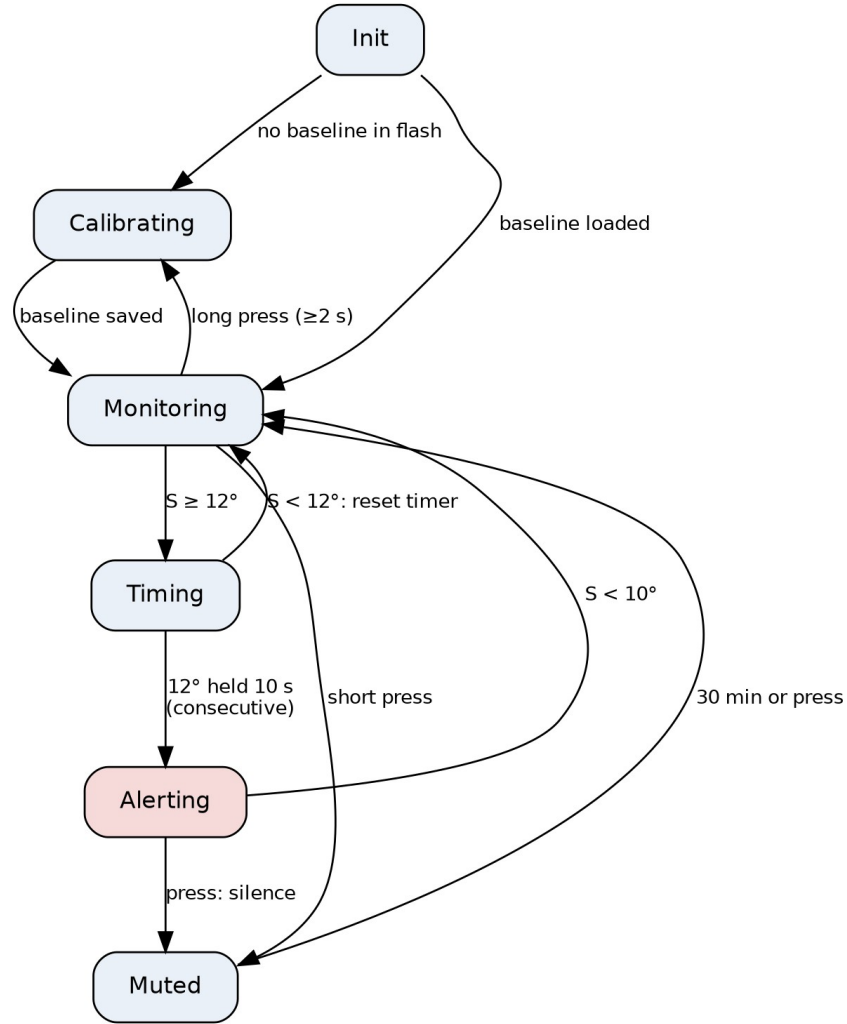


Figure 5: Firmware state machine. S is the strain metric of Equation (3); transitions use the 12° trigger, 10° release, 10 s dwell and 30 min mute defined above.

Timing and power. Per 10 ms cycle: I2C reads ≈ 0.8 ms, filter and logic (float math on the FPU) $\ll 0.1$ ms, so the MCU spends $> 90\%$ of each cycle in Sleep mode (woken by a timer), keeping average MCU current to roughly 3 mA (conservative). **Alert latency** after the 10 s dwell completes: ≤ 10 ms (next sample) + ≈ 100 ms (motor spin-up), far below the 1 s limit.

Requirements and Verification

Table 3: Processing and control subsystem requirements and verification

Requirement	Verification
The computed relative angle must be within $\pm 3^\circ$ of a reference at 0° , 15° , and 30° offsets.	After alignment and calibration, set relative pitch and roll to 0° , $\pm 15^\circ$ and $\pm 30^\circ$ with an independent jig. Record each axis for 10 seconds at each angle. Confirm maximum absolute quasi-static error $\leq 3^\circ$, and report mean and RMS error. Repeat after remounting and temperature tests described in Section 2.8.

Requirement	Verification
A true relative pitch/roll deviation $\geq 15^\circ$ held for 10 seconds must alert within 1 second afterward; detection must be $\geq 19/20$ in each positive-control group.	After neutral calibration, run 20 head-only trials (head $+15^\circ$, torso 0°), 20 torso-only trials (head 0° , torso -15°), and 20 combined trials (head $+20^\circ$, torso $+5^\circ$). Hold each for 12 seconds and return to neutral between trials. Use an independent reference and log dwell/alert timestamps. Pass: $\geq 19/20$ detections per group by 11 seconds. Repeat relative $\pm 15^\circ$ pitch and roll checks on the jig to verify both signs and axes.
Brief relative tilt, pure yaw, and common tilt with $\leq 5^\circ$ relative deviation must produce zero alerts in the specified negative-control trials.	Run 20 trials per condition: head-only $+20^\circ$ pitch for 5 seconds; torso-only -20° pitch for 5 seconds; head-only yaw $\pm 30^\circ$ for 15 seconds; torso-only yaw $\pm 30^\circ$ for 15 seconds; common head/torso $+20^\circ$ pitch for 15 seconds with relative pitch/roll $\leq 5^\circ$. Between trials hold neutral for 5 seconds and confirm the timer resets. Apply the brief-tilt and common-tilt tests in roll on the jig. Pass: zero alerts per group.
The calibration button must reset the baseline, persist across power cycles, and produce no false alerts for ≥ 5 min while the wearer stays upright and still.	Long-press to calibrate, power-cycle the device, and confirm the baseline is retained by reading it over UART. Then sit upright and still for 5 min and confirm no alert occurs.
A short press must mute alerts for 30 min, and a press during an alert must silence it.	Force an alert condition, short-press, and confirm the motor stops. Confirm no alerts for 30 min (use a shortened test constant for bench testing) and that alerts resume after.
Loop processing time must be < 2 ms per 10 ms cycle.	Toggle a GPIO at the start and end of each cycle's compute; measure duty on an oscilloscope.

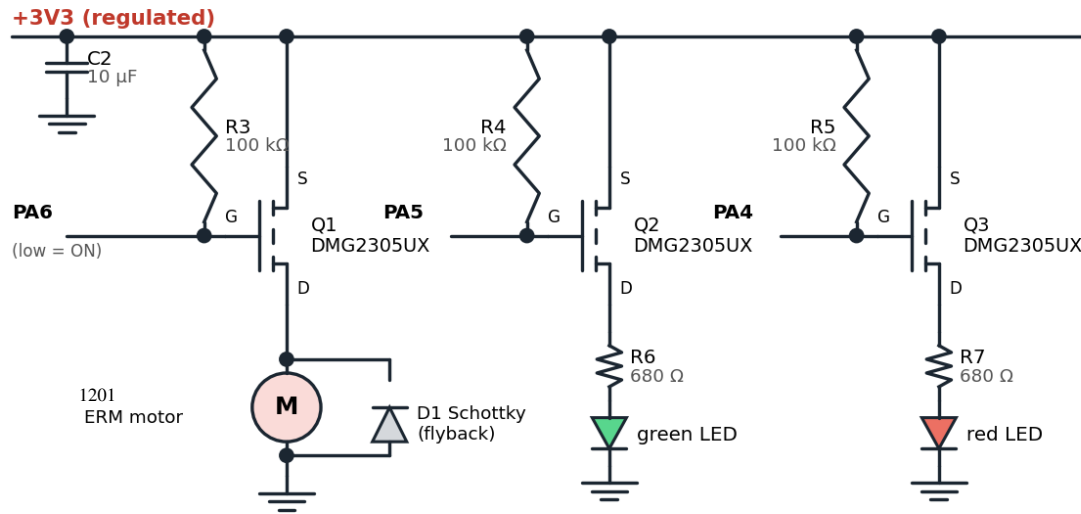
2.5 Feedback Subsystem

Role in the high-level requirements. Delivers the alert that HLR 1 triggers and HLR 4 requires the wearer to notice.

Design.

- Vibration motor: Adafruit 1201, a 10 mm coin ERM rated for 2.5–3.8 V (0.9 g), replaces the provisional 306-100. Purchase: <https://www.adafruit.com/product/1201>. The existing DMG2305UX high-side switch, 100 k Ω gate pull-up, flyback diode and 10 μ F rail capacitor remain. GPIO low turns the motor on. Measure steady current and startup peaks at 3.135–3.465 V; 100 mA is the steady-current design allowance, not a guaranteed motor specification. If exceeded, revise the current budget. Verify rail limits without MCU resets and turn-off spike ≤ 3.8 V. Motor and capacitor performance must be confirmed on the assembled circuit.
- Alert pattern: one 300 ms vibration pulse immediately upon alert entry, then at most one pulse every 6 seconds while the alert persists. A rolling 60-second motor-on-time budget of 3 seconds enforces $\leq 5\%$ duty, including repeated alert entries. If the budget is exhausted, retain the visible LED alert and resume vibration only when budget becomes available. Do not escalate to continuous vibration. Test first-alert noticeability after the motor budget has recovered; visibility remains the fallback during rate limiting.
- Status LEDs: separate green and red 0603 LEDs, each with its own DMG2305UX high-side switch and a 680 Ω current-limiting resistor (Figure 6), giving about 1.9 mA at 3.3 V; firmware never lights both at once. Use green pulses for monitoring, rapid green pulses for calibration, red pulses for alert, double red pulses for low battery, and alternating green/red pulses for mute. Limit

combined LED on-time to 10% at a maximum combined instantaneous current of 2 mA. This avoids requiring an unspecified amber LED and keeps the power budget consistent.



Motor on-time ≤ 3 s per rolling 60 s; LEDs lit one at a time: $I \approx (3.3 \text{ V} - 2.0 \text{ V}) / 680 \Omega \approx 1.9 \text{ mA}$, duty $\leq 10 \%$

Gate pull-ups (R3-R5) hold every MOSFET off while the MCU is in reset or still booting.

Figure 6: Feedback subsystem schematic: high-side P-channel MOSFET drive for the vibration motor (with flyback diode and 10 µF bulk capacitor) and for the green and red status LEDs.

Requirements and Verification

Table 4: Feedback subsystem requirements and verification

Requirement	Verification
The student-designed motor-drive circuit (DMG2305UX high-side switch, flyback diode D1, 10 µF bulk capacitor) must switch the motor on command while the 3.3 V rail stays within 3.135–3.465 V and the MCU does not reset over 100 consecutive pulses; D1 must limit the turn-off spike at the motor node to ≤ 3.8 V.	Measure steady and start-up motor current and the 3.3 V rail at full battery and near cutoff. Confirm 3.135–3.465 V throughout 100 pulses and no MCU reset. Probe the motor node on an oscilloscope and confirm the turn-off spike ≤ 3.8 V. Treat 100 mA as the steady-load allowance; measured start-up peaks set the final LDO/capacitor margin.
At least 8 of 10 test users must notice the alert within 3 s of triggering while performing a study task.	With the rolling motor budget recovered, trigger an alert during a reading/typing task for ten consenting volunteers. Confirm $\geq 8/10$ notice the first 300 ms pulse within 3 seconds. Separately hold an alert for 10 minutes and repeatedly re-enter alert: logged motor on-time must never exceed 3 seconds in any rolling 60-second window.
LED patterns must be distinguishable and visible indoors.	Cycle all patterns and have three observers identify each at arm's length indoors. Measure combined peak LED current ≤ 2 mA and combined duty $\leq 10\%$ over 60 seconds. Confirm the visible alert remains active when vibration is rate limited.

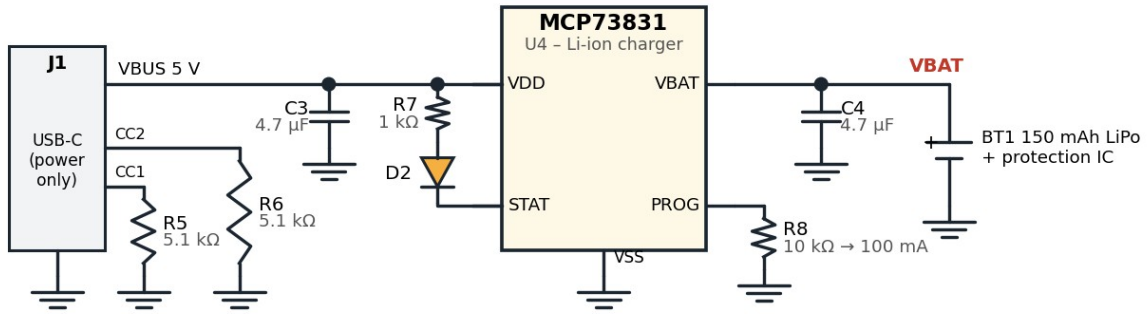
2.6 Power Subsystem

Role in the high-level requirements. Provides the 8 hour runtime (HLR 2) in a form factor that meets the weight and size limits (HLR 3).

Design.

- **Battery:** 3.7 V, 150 mAh LiPo with built-in protection circuit (Adafruit 1317 or equivalent) [11].
- **Charger:** MCP73831 single-cell linear charger [4] fed from a power-only USB-C receptacle (with 5.1 k Ω CC pull-downs). R_PROG = 10 k Ω sets I_charge = 1000 V / 10 k Ω = **100 mA ($\approx$ 0.67C)**, below the 1C limit for the cell, giving a charge time of roughly 1.5 to 2 hours. A charge-status LED is driven from the STAT pin.
- **Regulator:** AP2112K-3.3 LDO [5]. The firmware uses a loaded-battery cutoff of 3.65 V and a low-battery warning at 3.75 V. Budget 3.35 V for the upper regulated output, 0.20 V for dropout, 0.05 V for ADC/divider cutoff error, and 0.05 V for wiring and transient margin: 3.35 + 0.20 + 0.05 + 0.05 = 3.65 V. The datasheet lists maximum dropout of 0.20 V at 300 mA and 0.40 V at 600 mA under its stated test conditions; using 0.20 V at the intended ≤ 100 mA steady load is a conservative design allocation, not a guaranteed all-temperature specification at 100 mA. Measure motor startup peaks and validate rail regulation over 15–35°C. If the margin fails, raise the cutoff and repeat capacity/runtime tests, or revise the converter before claiming compliance.
- **Battery monitoring:** a 2×470 k Ω divider feeds an ADC pin. Use an appropriate acquisition time and a local filter capacitor, then calibrate against a multimeter to verify ≤ 50 mV battery-referred error. Sample at 10 Hz and during motor pulses, rather than once a minute. At ≤ 3.65 V disable the motor and enter low-power mode; resume monitoring only after charging above 3.85 V. Test residual shutdown current and ensure the cell protection circuit remains the final over-discharge safeguard.

Charging path



Regulation and battery monitoring

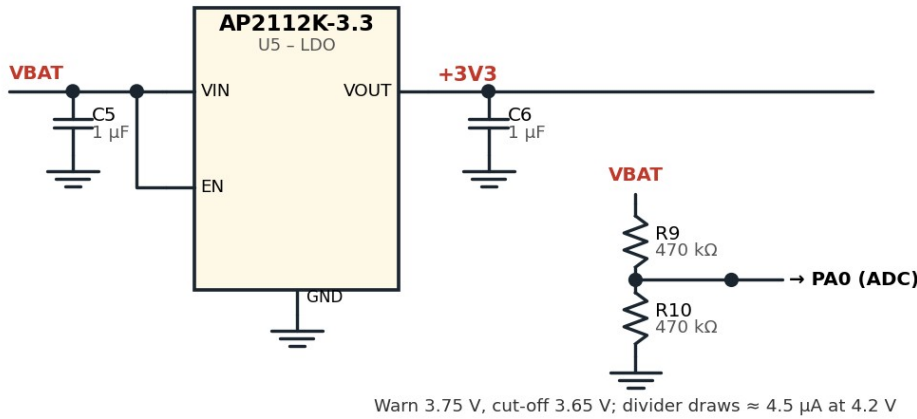


Figure 7: Power subsystem schematic: USB-C input with 5.1 kΩ CC pull-downs, MCP73831 charger ($R_8 = 10 \text{ k}\Omega$ sets 100 mA), protected 150 mAh LiPo, AP2112K-3.3 LDO and the battery-voltage divider to the ADC.

Power budget for continuous alerting with enforced 5% motor and combined LED duty, excluding optional BLE. Values are design estimates; verify actual current, including shutdown current and motor startup transients.

Table 5: Average current budget with the enforced 5% motor and LED duty

Load	Average current (mA)
STM32L452RE (16 MHz, mostly sleeping, conservative)	3.0
2 × ICM-42670-P (low-noise mode, $\sim 0.7 \text{ mA}$ each)	1.4
Vibration motor (100 mA design allowance $\times$ 5% duty)	5.0
LED (2 mA $\times$ 10% duty)	0.2
LDO quiescent and divider	0.06
Total	≈ 9.7

Usable capacity is the measured charge delivered from full charge to the actual loaded 3.65 V cutoff. With 100 mA motor current and enforced 5% motor duty, total estimated average current is 9.7 mA. Eight hours requires at least 77.6 mAh usable capacity (51.7% of nominal 150 mAh). A 90 mAh planning case gives 9.28 h; 75 mAh gives 7.73 h and fails. These are conditional calculations, not measured battery results. Test both cells on the final circuit; the lower measured runtime must be at least 8 h. If failed, revise load or battery/converter and recheck size and mass.

Requirements and Verification

Table 6: Power subsystem requirements and verification

Requirement	Verification
The rail must remain 3.135–3.465 V for loaded battery inputs of 3.65–4.2 V, intended steady loads ≤ 100 mA, and measured motor startup transients.	Test inputs 4.2, 3.8, 3.65 and 3.60 V at loads 0, 50 and 100 mA over 15–35°C; 3.60 V checks the lowest input allowed by a +50 mV cutoff reading error. Scope actual motor startups and include wiring losses. Pass the rail limits without resets. If failed, increase cutoff or revise power hardware, then repeat runtime testing.
The charger must charge the cell to 4.2 V $\pm$ 1% at $\approx$ 100 mA ($\pm$ 10%) and terminate automatically.	Start with the battery at $\approx$ 3.5 V and apply 5 V USB. Monitor charge current and cell voltage. Confirm peak current is 90–110 mA, the final voltage is 4.16–4.24 V, current tapers to near zero, and charge completes in < 2.5 h.
The final device must run ≥ 8 hours from full charge to firmware cutoff with the maximum permitted alert pattern, BLE off.	Fully charge the protected cell. Run continuous alert requests with 300 ms pulses every 6 seconds and LED duty $\leq 10\%$; log battery voltage and integrate measured battery current until the actual cutoff. Pass: runtime ≥ 8 hours and rail within limits until shutdown. Report Q_{usable} and I_{average} ; verify $Q_{\text{usable}} \geq 8 \text{ h} \times I_{\text{average}}$. Repeat on the spare cell and use the lower runtime. Use the full 5% motor-duty test.
Warn at 3.75 V and disable motor/enter low-power mode at 3.65 V, each with ≤ 50 mV battery-referred measurement error.	Ramp battery input through both thresholds at no motor load and during pulses. Compare ADC voltage to a multimeter; confirm thresholds within ± 50 mV, prompt motor disable, no repeated restart below 3.85 V, and shutdown current low enough for safe storage. Verify the protection circuit separately from the firmware cutoff.

2.7 Wireless Subsystem (Extra Goal)

A BLE module (STM32WB55CG or nRF52832 as a co-processor) connects to the MCU over UART. The MCU sends one record per second (timestamp, S, state) over a notification characteristic. A companion phone app stores the log and displays posture trends. The BLE radio is advertised only while the user enables it from the button, and sleeps between 1-second connection events, keeping average added current to well under 1 mA. This subsystem is implemented only if the core system is complete and verified ahead of schedule.

Table 7: Wireless subsystem requirements and verification (extra goal)

Requirement	Verification
The BLE link (MCU-to-module UART at 115 200 baud $\pm$ 2%) must deliver one posture record per second ($\pm$ 10%) to the phone app.	Pair a phone and confirm records arrive at 1 Hz in the app.
Data loss must be $< 5\%$ over a 30 minute continuous session.	Stream 1800 records with sequence numbers. Count missing sequence numbers on the phone; confirm ≤ 90 missing.

2.8 Tolerance Analysis

Critical interface: relative pitch/roll accuracy of the complete mounted device. High-level requirement 1 is only as good as the measured head-to-torso angle, and the 15° target versus the 12° firmware trigger leaves a 3° detection margin that the measurement error must stay inside. Table 8 gives the per-axis error budget for the two-sensor system. Entries marked as assumptions are datasheet-class values that the verification procedures of Sections 2.3 and 2.4 confirm on the built hardware.

Table 8: Per-axis relative-angle error budget

Error source	Basis	Per-axis relative error
Accelerometer noise	Design assumption: 100 $\mu\text{g}/\sqrt{\text{Hz}}$ and 40 Hz equivalent noise bandwidth. 0.63 mg per IMU corresponds to $\sim 0.036^\circ$; independent-noise RSS gives $\sim 0.05^\circ$. Measure stationary angle RMS over 60 seconds.	$\approx 0.05^\circ$ estimated RMS
Offset temperature drift (offset cancelled by baseline calibration; only drift remains)	Assumed 0.5 $\text{mg}/^\circ\text{C}$ over 10°C gives 5 mg ($\sim 0.29^\circ$) per sensor; aligned worst-case contributions sum to $\sim 0.58^\circ$. Initial offset is removed by calibration, but subsequent temperature drift is not.	$\leq 0.58^\circ$ allocated
Sensitivity and cross-axis error	Assumed sensitivity contribution 0.08° and cross-axis contribution 0.15° per sensor; sum across two sensors gives 0.46° . Validate mounted relative angles at 0° , $\pm 15^\circ$ and $\pm 30^\circ$.	$\leq 0.46^\circ$ allocated
Residual gyro bias (after startup bias calibration)	Target residual gyro bias $\leq 0.1^\circ/\text{s}$ per sensor. At $\tau=2$ s, per-sensor steady tilt error $\approx 0.2^\circ$; opposite-sign biases sum to 0.4° . During a 1-second accelerometer-correction freeze, additional relative drift can reach 0.2° .	$\leq 0.40^\circ$; $+0.20^\circ$ per 1 s freeze
Dynamic acceleration leaking through the accel path	Example: 0.1 g transverse acceleration gives $\text{atan}(0.1) \approx 5.7^\circ$ apparent tilt. A 0.5-second burst through a first-order 2-second correction path contributes $5.7^\circ(1 - \exp(-0.5/2)) \approx 1.26^\circ$ per sensor, potentially 2.52° relative. A magnitude-only acceleration gate can miss transverse acceleration: $\sqrt{1+0.1^2} - 1 \approx 0.005$ g. Therefore motion immunity requires tests, not this gate alone.	$\approx 2.52^\circ$ transient example
Static subtotal excluding mounting and random noise	Temperature + sensitivity/cross-axis + gyro allocations: $0.58^\circ + 0.46^\circ + 0.40^\circ = 1.44^\circ$. Add mounting allocation below; keep random RMS noise and motion transients separate.	1.44° allocated
Mounting alignment and clip slip	Allocate $\leq 1.0^\circ$ total relative mounting error after alignment and during normal wear. Constant neutral offset can be calibrated; axis rotation and later slip cannot be assumed to cancel. Test five removal/remount cycles with recalibration, 30 minutes of wear, and deliberate 1° , 3° , 5° clip shifts.	$\leq 1.0^\circ$ acceptance target

Conclusion. The static allocations sum to $0.58^\circ + 0.46^\circ + 0.40^\circ + 1.0^\circ = 2.44^\circ$. Adding 3 times the estimated RMS noise (0.15°) gives a 2.59° planning envelope, leaving 0.41° against the $\pm 3^\circ$ target (Figure 8). This is conditional on the stated component, calibration and mounting assumptions. A 3σ allowance is statistical, not an absolute error bound or proof of every trial passing. Within this envelope a true 15° tilt reads at least 12.41° , above the 12° trigger; a 5° offset reads at most 7.59° . The specified 0.1 g, 0.5 s motion burst can add about 2.52° relative transient error. At a 5° starting offset this gives at most 10.11° , below the trigger, under this example model. Longer or repeated motion requires measurement.

Dynamic motion can interrupt the 10 s dwell and delay detection. Verify the alert deadline for sustained quasi-static tilt after reaching the reference position, not during arbitrary motion. Transient errors are excluded from the quasi-static $\pm 3^\circ$ test and are assessed separately in the specified brief-tilt, yaw and common-tilt trials. If measured error exceeds 3° , clip slip exceeds 1° , or motion produces false alerts, revise mounting/filtering and repeat verification.

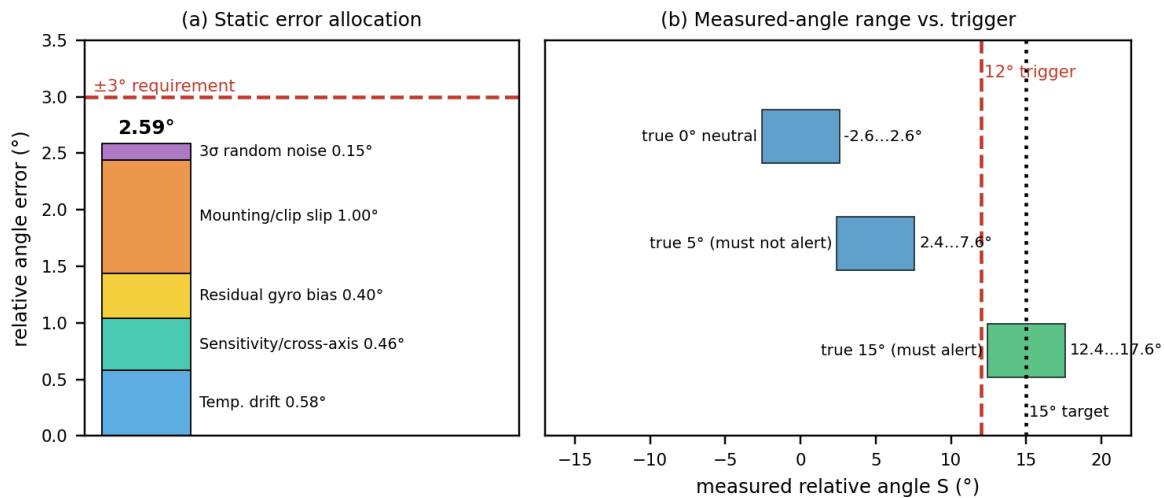


Figure 8: Tolerance analysis. (a) Static error allocation against the $\pm 3^\circ$ requirement. (b) Range of the measured relative angle for true tilts of 0° , 5° and 15° , with the 12° trigger.

Bias and mounting verification. Log each gyro axis while stationary for 60 seconds before and after the 3-second calibration; target residual mean $\leq 0.1^\circ/\text{s}$ per IMU. Repeat at 15°C , 25°C and 35°C after thermal settling. Use an independent angle jig for mounting and motion tests. After a deliberate post-calibration slip, quantify the change in relative estimate; for pure pitch slip, a 3° or 5° sensor rotation can mimic approximately 3° or 5° of neck angle. Require recalibration after a displaced clip and do not claim automatic slip detection.

Timing tolerance. The internal 16 MHz oscillator has about $\pm 1\%$ accuracy, so the 10 s dwell is accurate to about ± 0.1 s, within the ± 0.5 s allowed in verification.

3 Cost and Schedule

3.1 Cost Analysis

Labor. Assuming a reasonable starting ECE salary of \$40/hour, 100 hours of work per person over the semester, and the course 2.5 multiplier:

$\$40/\text{hr} \times 2.5 \times 100 \text{ hr} = \$10,000$ per team member. For three members: **\$30,000**.

Parts. Prices are budgetary estimates from typical distributor pricing for the quantities shown; each purchase link opens the distributor product or search page used for ordering. The custom main PCB and glasses sensor PCB are excluded from the \$150 parts budget, as specified by the course. No machine-shop labor is required because the enclosures are 3D printed.

Table 9: Bill of materials (excluding custom PCBs)

#	Description	Manufacturer / part #	Qty	Unit	Extended	Purchase link
1	6-axis IMU	TDK InvenSense ICM-42670-P	3	\$2.80	\$8.40	DigiKey
2	MCU	STMicroelectronics STM32L452RET6	2	\$8.20	\$16.40	DigiKey
3	Dev board (firmware prototyping)	STMicroelectronics NUCLEO-L452RE-P	1	\$14.50	\$14.50	DigiKey
4	IMU breakout board, 3.3 V with on-board regulator	ICM-42670-P breakout (Lectronz)	2	\$12.00	\$24.00	Lectronz
5	Vibration motor	Adafruit 1201	2	\$1.95	\$3.90	Adafruit
6	3.7 V 150 mAh LiPo with protection	Adafruit 1317	2	\$5.95	\$11.90	Adafruit
7	LiPo charger IC	Microchip MCP73831T-2ACI/OT	3	\$0.65	\$1.95	DigiKey
8	3.3 V LDO	Diodes Inc. AP2112K-3.3TRG1	3	\$0.50	\$1.50	DigiKey
9	P-channel MOSFET (motor, 2 LEDs)	Diodes Inc. DMG2305UX-7	6	\$0.35	\$2.10	DigiKey
10	Schottky diode (flyback)	Diodes Inc. B5819W-7-F	4	\$0.30	\$1.20	DigiKey
11	Tactile push button, SMD	C&K PTS810 SJM 250 SMTR LFS	5	\$0.20	\$1.00	DigiKey
12	0603 LED, green	Lite-On LTST-C190KGKT	5	\$0.15	\$0.75	DigiKey
13	0603 LED, red	Lite-On LTST-C190KRKT	5	\$0.15	\$0.75	DigiKey
14	USB-C receptacle, 6-pin power-only	GCT USB4125-GF-A	3	\$0.70	\$2.10	DigiKey
15	Passives: 0402/0603 resistors and capacitors per Figures 5–7	See detailed parts on p. 17; Yageo / Samsung / KEMET	1 lot	\$8.00	\$8.00	DigiKey
16	Glasses-board header and cable connectors; 30 AWG 4-conductor wire	JST SM04B-SRSS-TB, SHR-04V-S-B	1 lot	\$6.00	\$6.00	DigiKey
17	3D-printed enclosures (PETG filament)	n/a (printed in-house)	1 lot	\$6.00	\$6.00	n/a
18	SWD programming header, 10-pin 1.27 mm	Samtec FTSH-105-01-L-DV-K	1 lot	\$3.00	\$3.00	DigiKey
19	Glasses-arm clip, tape, mounting hardware	Generic hardware	1 lot	\$4.00	\$4.00	n/a
	Parts subtotal				\$117.45	
	Shipping (5%)				\$5.87	
	Sales tax (10%)				\$11.75	
	Parts total (excl. PCB)				\$135.07	

The parts total of \$135.07 is under the \$150 budget, leaving about \$14.93 for replacements. *Non-standard items:* lab equipment (oscilloscope, programmable load, bench supply, ST-Link/SWD programmer, soldering and reflow stations) is provided by the ECE 445 lab at no cost to the team. PCB fabrication is excluded from the budget, and no machine-shop labor is needed.

Total project cost: \$30,000 (labor) + \$135.07 (parts) = \$30,135.07 (excluding PCB fabrication).

3.2 Schedule

Table 10 assigns exactly one task to each team member each week. Dates are the planned target weeks for fall 2026.

Table 9 (continued): Detailed passive-component BOM

Value / purpose	Manufacturer / part number	Qty*	Est. cost	Purchase
2.2 k Ω ; I ² C pull-ups	Yageo RC0603FR-072K2L	3	\$0.30	Buy / lookup
5.1 k Ω ; USB-C CC	Yageo RC0603FR-075K1L	3	\$0.30	Buy / lookup
10 k Ω ; PROG / button	Yageo RC0603FR-0710KL	3	\$0.30	Buy / lookup
100 k Ω ; MOSFET gates	Yageo RC0603FR-07100KL	4	\$0.40	Buy / lookup
470 k Ω ; battery divider	Yageo RC0603FR-07470KL	3	\$0.30	Buy / lookup
680 Ω ; green/red LEDs	Yageo RC0603FR-07680RL	3	\$0.30	Buy / lookup
1 k Ω ; charge LED	Yageo RC0603FR-071KL	2	\$0.20	Buy / lookup
100 nF; IMU / ADC filter	KEMET C0603C104K4RACTU	4	\$0.52	Buy / lookup
1 μ F; LDO input/output	Samsung CL10A105KB8NNNC	4	\$0.60	Buy / lookup
4.7 μ F; charger input/output	Murata GRM188R61E475KE11D	4	\$0.96	Buy / lookup
10 μ F; motor rail bulk	Samsung CL21A106KAYNNNE	2	\$0.70	Buy / lookup

*Quantities include small spares; resistors are 0603, $\pm 1\%$, ≥ 0.1 W.
 Capacitors: X7R/X5R ceramic; 100 nF ≥ 16 V, 1 μ F ≥ 10 V, 4.7 μ F ≥ 10 V,
 10 μ F ≥ 10 V. Confirm effective capacitance under DC bias and footprints.
 The original \$8 passive allocation covers these estimates plus spare allowance;
 it is retained in the cost total. Purchase prices are estimates, not checkout quotes.

Motor replacement: Adafruit 1201 (10 mm diameter, 2.7 mm thick, 0.9 g).
 Rated supply: 2.5–3.8 V. <https://www.adafruit.com/product/1201>
 Verify startup, steady current and noticeability with the existing driver.

The ADC filter capacitor is added at PA0 to ground. Select sufficient ADC
 acquisition time for the 470 k Ω /470 k Ω divider; verify ≤ 50 mV battery error.
 Manufacturer pin connections, decoupling and footprints are checked against
 datasheets before PCB fabrication. Retain the existing schematic topology.

Table 10: Weekly schedule with one task per team member

Week	Hrishikesh	Praveen	Heet
Oct 5 – Oct 11	Finalize estimator architecture and firmware spec	Finalize power architecture; order prototyping parts	Define enclosure constraints and angle-test jig plan
Oct 12 – Oct 18	Bring up I ² C and read both IMUs on the Nucleo	Capture main-board schematic	Breadboard motor and LED drive circuits
Oct 19 – Oct 25	Implement complementary filter and relative angle	Design charger and LDO circuit; verify power calculations	Capture glasses-board schematic; enclosure CAD v1
Oct 26 – Nov 1	Implement calibration routine and flash storage	Lay out main PCB	Lay out glasses PCB; build angle-test jig
Nov 2 – Nov 8	Implement dwell timer, mute and state machine	PCB design audit and first PCB order	Print first enclosure; fit check
Nov 9 – Nov 15	Port firmware to the custom PCB over SWD	Assemble and bring up power, MCU and IMU	Assemble glasses board and feedback circuits
Nov 16 – Nov 22	Run detection and false-alert trials	Run rail and battery runtime tests	Fix PCB issues; second order if needed
Nov 23 – Nov 29	Run temperature and remount tolerance tests	Final enclosure; weight and size verification	Run alert-noticeability study with 10 users
Nov 30 – Dec 6	Fix remaining firmware bugs	Run the full R&V tables	Prepare demo setup; finalize safety checklist
Dec 7 onward	Demo (firmware)	Final presentation	Final report

4 Discussion of Societal Impact, Engineering Standards, Ethics, and Safety

4.1 Societal Impact

Public health. Chronic neck and back pain are common among students and desk workers. A low-cost device that gives real-time feedback helps people form better posture habits before pain starts. **Economic.** At roughly \$139 in prototype parts (and far less at volume), with no subscription, it is accessible to students on a budget. **Environmental.** It uses a rechargeable cell and no cloud service, avoiding disposable batteries and the electronics churn of subscription gadgets. **Social and cultural.** The device uses no camera or microphone and works entirely on-device, so it can be worn in classrooms, libraries, and offices without privacy objections. It can be worn discreetly by a wide range of users. **Global.** The design relies on commodity components and requires no network connectivity, so it works anywhere.

4.2 Engineering Standards

- **I2C-bus specification (NXP UM10204) [7]:** Fast Mode timing, rise time and pull-up sizing.
- **IEC 62133-2 [12]:** informs rechargeable-cell safety selection. Integrated protection alone does not demonstrate certification. Obtain supplier compliance documentation before claiming that the selected battery meets this standard.
- **USB Type-C specification [19]:** CC pull-down requirement for sink-only devices.
- **IPC-2221 / IPC-A-610 [20]:** PCB design and assembly workmanship.
- **FCC Part 15 [21]:** applies to unintentional radiators, and to the intentional radiator (BLE) if the extra goal is implemented; a pre-certified module would be used.
- **Bluetooth Core Specification (BLE) [22]** for the extra goal.
- **ISO 10993-1 (biological evaluation of medical devices) [23]:** informs material choices for skin contact; we avoid claiming medical use.

4.3 Ethics

We follow the **IEEE Code of Ethics** [8] and the **ACM Code of Ethics** [9]. Relevant provisions:

- **IEEE I.1** (hold paramount the safety, health, and welfare of the public): addressed through battery protection, a breakaway cable, and low-voltage design.
- **IEEE I.5** (be honest and realistic in stating claims): the device is a *posture reminder*, **not a medical device**. We will not claim it prevents or treats neck pain or injury, and will report measured detection rates honestly, including false alerts and failures.
- **ACM 1.6 (respect privacy)** and **1.7 (honor confidentiality)**: the device collects no images or audio and stores only angle data; calibration data stays in on-chip flash. If the BLE extra goal is implemented, posture logs are sent only to the user's own phone, with no cloud storage, and the user chooses when to enable it.
- **Inclusivity**: users have different body types and posture; the per-user calibration baseline addresses this rather than assuming a single "correct" posture.

4.4 Safety Concerns and Mitigation

This section follows the ECE 445 Safety Guidelines [17] and the course lithium-battery guidance [18]. The device contains a lithium cell worn near the neck, which makes the battery the dominant hazard. Table 11 lists each concern and its mitigation.

Table 11: Safety concerns and mitigations

Concern	Mitigation
LiPo battery fire, swelling, or short circuit (the cell sits near the user's neck)	Use only a commercial cell with an integrated protection circuit (over-charge, over-discharge, over-current). Charge at $\leq 0.67C$ through a dedicated charger IC. Never charge while the device is worn; the USB-C port is used only when the device is off the body. Enclose the cell so terminals cannot be shorted. During development, charge and store cells in a LiPo-safe bag on the bench, never unattended, and follow the ECE 445 battery safety guidelines. Inspect cells for swelling and replace them if damaged.
Cable snagging or pulling on the neck	Cable length ≤ 30 cm of thin, light wire, routed along the glasses temple and collar. A breakaway friction-fit connector near the collar releases under a modest pull.
Skin contact (vibration, heat, material irritation)	Low-voltage design (≤ 4.2 V everywhere). The 150 mAh cell limits available energy. Motor duty is capped. Enclosures printed in a skin-friendly material (e.g., PETG or nylon) with rounded edges and a fabric or foam backing.
Distraction or startle from the vibration	Vibration is short, brief, and low-amplitude, and the wearer can mute it with one press.
Electrical hazards during development	All voltages are ≤ 5 V; use ESD protection at the workbench, follow lab soldering and ventilation rules, and use the lab's current-limited bench supplies when testing power circuits.
Unsupported health claims	The documentation and demo describe the device only as a posture reminder.

Because the project involves a lithium cell worn on the body, the battery lab safety checklist in Section 4.5 accompanies this design review, and the team complies with the course safety guidelines [17], [18]. No high-voltage, aerial, or chemical hazards are present, so no separate Safety Manual is required.

Concerns that arose since the proposal. (1) Pack protection alone is not treated as the discharge limit; the firmware cuts the motor off at 3.65 V and the cell's protection IC is only the last safeguard. (2) A rolling motor on-time budget (3 s per 60 s) limits heating and distraction. (3) A clip that slips after calibration could silently shift the measured angle, so the device requires recalibration after any remount and the documentation does not claim automatic slip detection. (4) Charging is allowed only with the

device off the body. (5) The cable uses a breakaway connector so a snag releases rather than pulling on the wearer.

4.5 Battery Lab Safety Checklist

- **Before use:** read the cell's datasheet and safety data; confirm the Adafruit 1317 cell has its protection circuit; inspect for swelling, dents, or damaged leads. Never use a damaged cell.
- **Approvals and rules:** have the TA and course staff review the battery, charging circuit and storage bag before first power-up; complete the mandatory lab safety training; never work in the lab alone [17], [18].
- **Charging:** use only the MCP73831 charger board at 100 mA ($\approx 0.67C$); charge attended, on a non-combustible surface, inside a LiPo-safe bag, with the device off the body; stop immediately if the cell becomes noticeably warm.
- **Runtime testing:** the 8-hour test runs inside a LiPo-safe bag with a second person aware of it; log battery voltage and stop if the cell temperature exceeds 45 °C.
- **Storage:** store at partial charge (about 3.8 V) in a LiPo-safe bag away from flammable material; never carry loose cells with metal objects.
- **Incidents and disposal:** if a cell swells, smokes, or gets hot, disconnect it if safe, place it in the LiPo bag away from flammables, and notify the TA and course staff immediately; take spent or damaged cells to the campus battery-recycling or hazardous-waste collection rather than the trash.

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