

ECE 445 Senior Design Lab Proposal: Non-Shock Ultra-Wideband Virtual Boundary Pet Collar

Team Number: 002

Team Members:

Yujia (Peter) Gao (peterg4)

Shi Xian Chng (schng2)

Shi Yang Ng (syng2)

Teaching Assistant: Tianda Huang (tiandah2)

1. Introduction

1.1 Problem

Some areas of a home, such as kitchens and workshops, should be kept clear of pets. Physical barriers can also obstruct people, while indoor virtual boundaries need to work at room and doorway scales where GPS and signal-strength estimates may be unreliable. Our project uses vibration and sound cues to discourage pets from approaching a boundary without electric shocks.

1.2 Solution

Wall-powered UWB anchors form a chain, with each adjacent pair defining a finite boundary segment. The collar estimates its distance to the nearest segment and gives vibration followed by a tone as it approaches from either side; it does not distinguish inside from outside. We plan to demonstrate up to four anchors, automatic spacing surveys, and no central hub. The collar runs on a battery and charges over USB-C only while switched OFF and removed from the pet.

1.3 Visual Aid

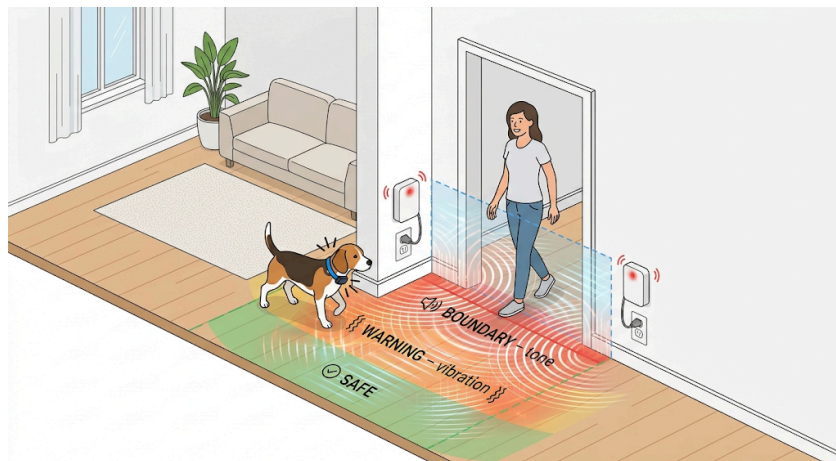


Figure 1. Intended use of the virtual boundary in a home.

1.4 High-Level Requirements

- **Accuracy:** boundary-distance RMS error ≤ 0.5 m at 10 measured positions, including doorway and obstructed-path tests.
- **Responsiveness:** start the motor/buzzer drive within 50 ms of entering the warning zone, escalate from vibration to tone, and avoid repeated switching during a 15-minute stationary hysteresis test.
- **Safety and wearability:** stop feedback after 10 seconds of continuous boundary dwell, target 24 hours of ranging without feedback events per charge, and keep the assembled collar under 60 g.

2.1 Block Diagram

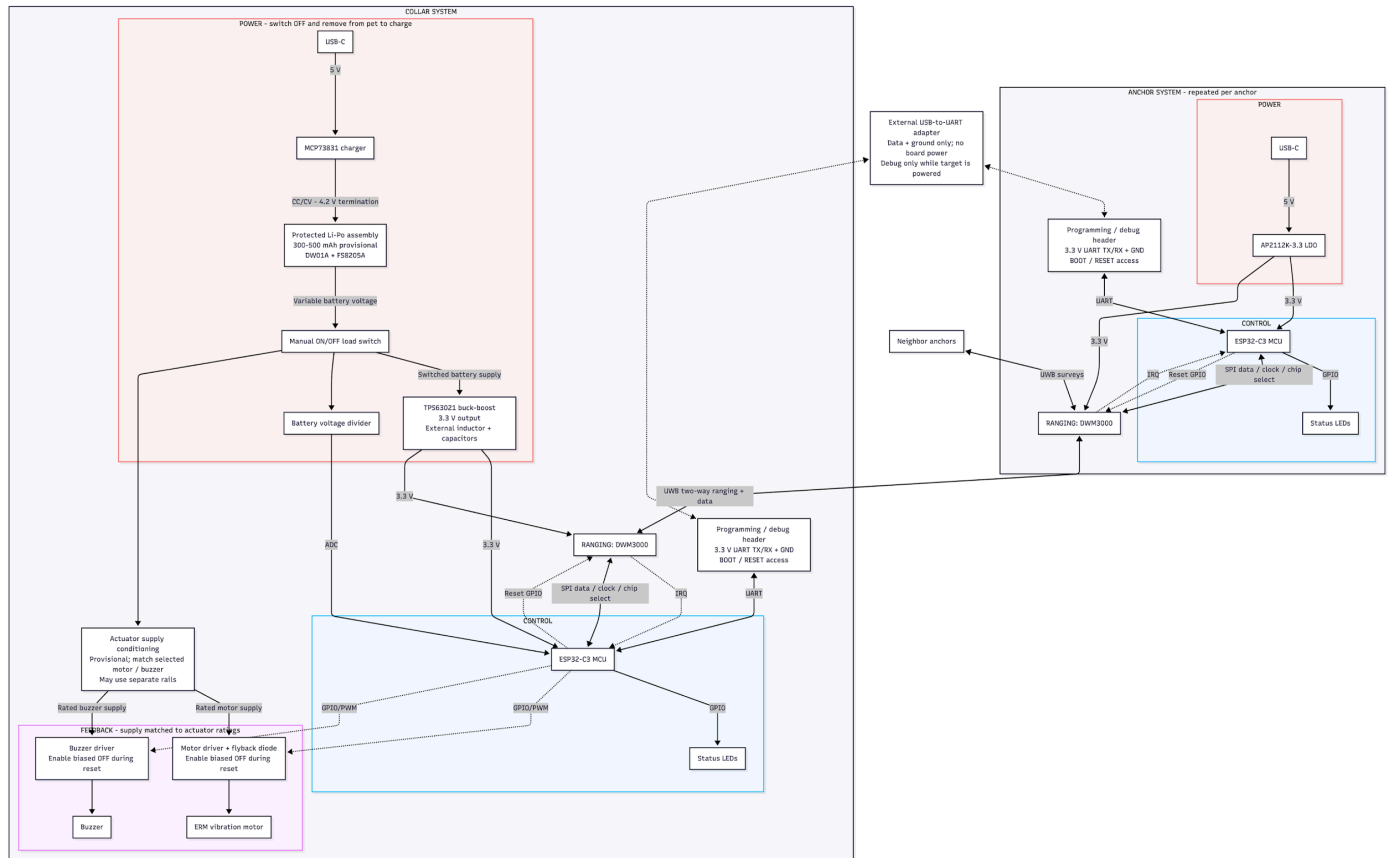


Figure 2. Hardware architecture, including power supplies, actuator drivers, and debug connections.

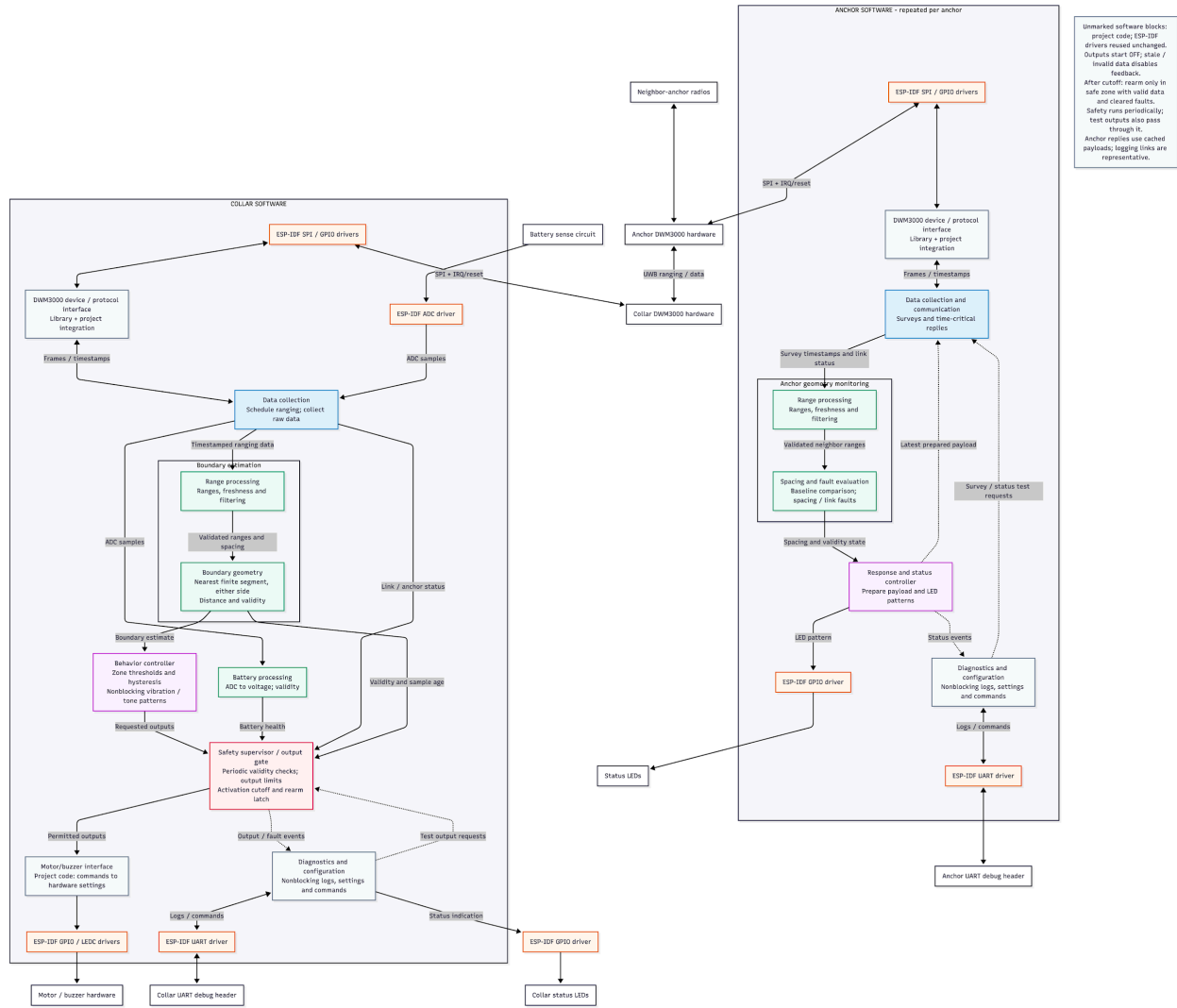


Figure 3. Software architecture: collection and estimation feed behavior, safety, and actuation; diagnostics support both devices.

2.2 Subsystem Overview

Both devices use an ESP32-C3-MINI-1 and DWM3000 connected by SPI, interrupt, and reset signals [7], [8]. We plan a shared PCB with different components populated for each role. We will write the application and actuator interface, reuse ESP-IDF peripheral drivers, and integrate a DWM3000 library. Diagnostics handle logs, settings, test commands, and status LEDs through separate 3.3 V UART headers; the external adapter supplies no power. BLE telemetry and phone notifications remain stretch features.

Anchor

- Ranging.** Answer addressed collar requests using double-sided two-way ranging and survey neighboring anchors between exchanges. Replies include cached spacing, age, and fault information so they do not wait for a new survey.

- **Control.** Process survey data, compare neighbor spacing with the setup baseline, and prepare response payloads and LED patterns. Changed spacing or missing neighbors raises a fault. Repositioning requires recalibration; movement that preserves neighbor spacing cannot be detected.
- **Power.** A USB-C wall adapter supplies 5 V, regulated to 3.3 V by an AP2112K-3.3. Battery and charging components are not populated on anchors.

Collar

- **Ranging.** Poll up to four anchors by ID and collect timestamps, spacing, and fault information. Boundary estimation validates the ranges and selects the nearest finite segment. Battery readings are processed separately.
- **Control.** The behavior controller selects zones, applies hysteresis, and requests vibration or tone patterns. A periodic safety gate limits or disables these requests before the actuator interface calls GPIO/PWM drivers. Outputs start OFF and mute on stale or invalid data, anchor faults, or low battery. After the 10-second cutoff, feedback requires a return to the safe zone with valid data and cleared faults. Debug commands use the same safety gate.
- **Feedback.** An ERM motor provides vibration and a buzzer provides sound. GPIO/PWM drivers remain OFF during reset and use conditioned power downstream of the load switch. The motor includes a flyback diode. Actuator parts and supply conditioning will be selected together.
- **Power.** A proposed 300–500 mAh Li-Po uses an MCP73831 charger and DW01A/FS8205A protection. A manual switch disconnects operating loads while leaving the charger connected to the protected battery terminals. A TPS63021 supplies the 3.3 V MCU/UWB rail [9]; actuator power and battery sensing are also switched. Charging requires the collar OFF and removed from the pet, with no automatic interlock or simultaneous operation.

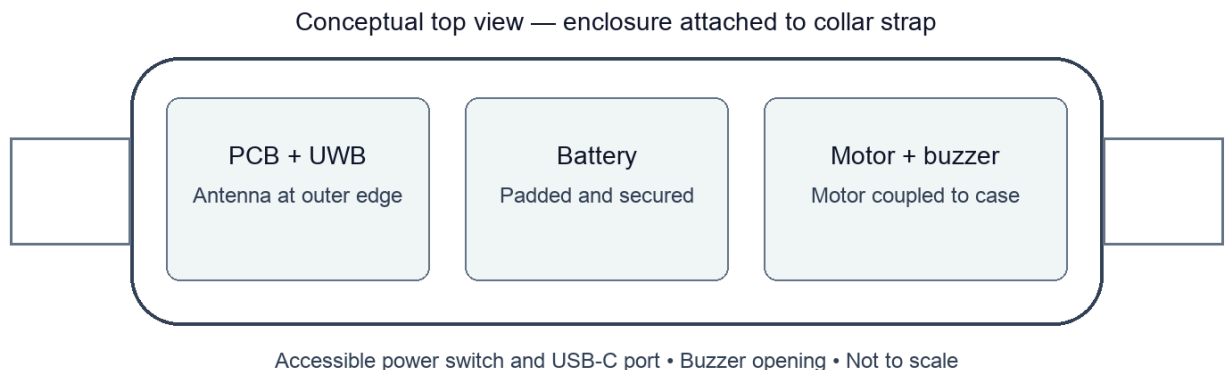


Figure 4. Proposed collar packaging; layout and dimensions will be refined after component selection.

2.3 Subsystem Requirements

These are preliminary prototype targets, not measured results. The baseline polls four anchors every 25 ms (40 Hz), with sleep between exchanges where possible. Component choices, thresholds, and scheduling will be refined during testing.

Table 1. Anchor - Ranging

Requirement	Verification
Responds to a poll addressed to its ID within 5 ms, and never responds to other IDs.	Measure response delay over 100 addressed polls using radio timestamps or a logic analyzer; confirm no replies to 100 wrong-ID polls.
Self-surveyed neighbor spacing has RMS error ≤ 0.10 m at 1–5 m.	At 1, 3, and 5 m spacing, compare 50 logged survey estimates with tape measurements.
Enters fault state within 10 s if surveyed spacing changes by more than 0.3 m.	Change neighbor spacing by 0.5 m and time the fault LED and response flag.

Table 2. Anchor - Control

Requirement	Verification
Boots and begins responding to polls within 5 s of power-on.	Time from USB-C plug-in to first valid response seen by collar.
Status LEDs distinguish OK / surveying / fault.	Force each state via debug command; visually confirm LED pattern.

Table 3. Anchor - Power

Requirement	Verification
3.3 V rail stays within $\pm 5\%$ from no load to peak load (UWB TX + MCU active).	Scope the rail during a burst of 100 ranging exchanges; record min/max.
Operates from any 5 V USB source between 4.5 V and 5.5 V.	Power from bench supply at 4.5 V and 5.5 V; confirm ranging works.

Table 4. Collar - Ranging

Requirement	Verification
Point-to-point RMS range error ≤ 0.30 m at 1–5 m line of sight, and ≤ 0.50 m through a doorway or with a person in the path.	Collect 50 samples at each of 10 measured positions; calculate RMS error separately for clear and obstructed paths.
Completes a full four-anchor ranging cycle within each 25 ms period.	Log 100 complete four-anchor cycles with neighbor surveys enabled; check all IDs respond within each 25 ms period.

Table 5. Collar - Control

Requirement	Verification
Boundary-distance RMS error ≤ 0.5 m at each of 10 tape-measured positions, including a doorway and obstacles. (HLR 1)	Compare 50 estimates at each of 10 marked positions with the nearest segment, including both sides and beyond endpoints.
The motor/buzzer drive command starts within 50 ms of crossing into the warning zone. (HLR 2)	Move the collar across a marked threshold and compare crossing time with the drive signal over repeated passes.
No repeated safe/warning toggling during 15 min stationary within the configured hysteresis band. (HLR 2)	Enter the hysteresis band from each side and hold for 15 min; confirm no repeated switching, then check both band limits.
Outputs start OFF; feedback stops by 10 s of continuous boundary dwell and within 2 s of stale/missing ranging data. Invalid geometry or anchor faults disable feedback on the next safety check. (HLR 3)	Check startup, boundary dwell, anchor loss, and injected invalid data/faults. Time shutdown and verify the stated rearming conditions.
Mute feedback near a preliminary 3.2 V battery cutoff, measured by divider and ADC. Set the final threshold and recovery hysteresis for the chosen cell; hardware protection is a backup.	Sweep a current-limited battery substitute down and up; compare ADC readings with a meter and check cutoff and recovery.

Table 6. Collar - Feedback

Requirement	Verification
Motor vibration reaches 90% of its steady-state amplitude within 100 ms after the drive command.	Use an accelerometer to compare vibration rise with the drive signal, separately from command latency.
Buzzer produces ≥ 70 dB at 10 cm.	SPL meter at 10 cm.

Table 7. Collar - Power

Requirement	Verification
The 3.3 V rail stays within $\pm 5\%$ over a proposed 3.2–4.2 V battery range, including peak MCU/UWB load and actuator switching.	Sweep a battery substitute from 4.2 to 3.2 V and scope the rail during ranging and feedback.
≥ 24 hr runtime with ranging active and no feedback events. (HLR 3)	Run four-anchor ranging at 40 Hz with surveys, no feedback, BLE off, and UART disconnected. Measure average current and time to operating cutoff.
USB-C charging works with the collar OFF and removed from the pet. Estimate 2–3 hours at about 0.5C, subject to the chosen cell and charger limits [10].	Record charge current, cell voltage, and time to termination. Confirm operating loads remain off with USB connected and disconnected.

Requirement	Verification
Battery protection provides backup undervoltage and overcurrent shutdown appropriate to the selected cell.	Use a battery simulator and controlled load to check protection trips against the selected circuit specifications.
Assembled collar (PCB + battery + enclosure + strap) < 60 g. (HLR 3)	Scale.

2.4 Tolerance and Feasibility

Range errors are amplified near the line between two anchors. This estimate shows how anchor spacing affects boundary accuracy and guides our first tests.

For anchors separated by L and collar ranges r_1 and r_2 , assume the anchors are mounted near collar height. The position along the anchor line and perpendicular distance are:

$$x = (r_1^2 - r_2^2 + L^2)/(2L), \quad d = \sqrt{(r_1^2 - x^2)}. \quad (1)$$

For a finite segment, use d when $0 \leq x \leq L$ and the distance to the nearer endpoint otherwise. Invalid geometry disables feedback.

For a collar centered between the anchors, independent small range errors σr and spacing error σL give the first-order estimate:

$$\sigma d^2 \approx [(L^2/4 + d^2)/(2d^2)]\sigma r^2 + [L^2/(16d^2)]\sigma L^2. \quad (2)$$

Table 8. Estimated boundary-distance uncertainty for two anchor spacings (assumed input errors).

Spacing L	Distance d	Range error σr	Spacing error σL	Estimated σd
4 m	0.3 m	0.10 m	0.10 m	0.58 m
2 m	0.3 m	0.10 m	0.10 m	0.30 m

The 2 m case is below the 0.5 m accuracy target under these assumptions, making shorter spacing a useful starting point. The 4 m case exceeds it near the boundary, although its estimated error at the 1 m warning threshold is about 0.19 m.

This approximation does not establish real-world accuracy: obstructions, height differences, and systematic bias need testing, and the model becomes unreliable very near the anchor line.

We will start with warning and boundary thresholds near 1.0 m and 0.3 m, then tune spacing, hysteresis, and filtering. Long averaging windows may improve random noise but add delay and do not remove systematic bias.

Timing. A 25 ms four-anchor cycle leaves about 25 ms for processing and the drive command within the 50 ms target. Neighbor surveys must fit between collar exchanges. The separate 100 ms motor-rise target allows roughly 150 ms from crossing to near-steady vibration.

Power. A 300–500 mAh, 3.7 V cell with roughly 80% usable capacity and 85–90% conversion efficiency provides about 0.8–1.3 Wh. A 24-hour runtime therefore requires roughly 10–17 mA average on the 3.3 V rail, before other loads. At 30 mA, runtime would be only about 8–13 hours. We will measure the MCU/radio duty cycle early; achieving 24 hours at 40 Hz remains an open design question.

3. Ethics, Safety, and Societal Impact

Animal welfare. Vibration and sound avoid electric shock, while the activation cutoff and fault shutdown aim to reduce unintended stimulation. We will evaluate feedback on the bench first; these safeguards do not by themselves establish animal comfort or training effectiveness. This follows the harm-prevention intent of the IEEE Code of Ethics [1].

Societal impact. The boundary could help keep pets away from selected areas while leaving passages clear for people. It cannot guarantee containment and should not replace a physical barrier where failure could expose a pet to danger.

Electrical and physical safety. A protected Li-Po and CC/CV charger will follow cell guidance and lab procedures [2], [3]. Charging is off-only and away from the pet. The enclosure will shield the battery from sharp edges, secure wiring, and provide strain relief; fit and comfort remain to be assessed.

Radio operation. We will follow module guidance and applicable UWB limits [4]. Operating settings and wearable RF exposure still need review; selecting a module alone does not establish compliance.

Table 9. Applicable standards

These standards guide the design; compliance has not yet been verified.

Standard / Specification	Application	References
IEEE Code of Ethics	Ethical engineering practices and harm prevention	[1]
IEC 62133-2 / UL 1642	Lithium cell operational and handling safety	[2], [3]
FCC 47 CFR Part 15 Subpart F	Ultra-Wideband (UWB) emission limits	[4]
IEEE 802.15.4-2020 / 802.15.4z	HRP UWB PHY and ranging protocols	[5]
USB 2.0 / USB Type-C	Power delivery and connector specifications	[6]

4. References

- [1] IEEE, "IEEE Code of Ethics," IEEE Policies, Sec. 7.8. [Online]. Available: <https://www.ieee.org/about/corporate/governance/p7-8.html>
- [2] Secondary cells and batteries containing alkaline or other non-acid electrolytes - Part 2: Lithium systems, IEC 62133-2:2017, IEC, 2017.
- [3] Standard for Lithium Batteries, UL 1642, Underwriters Laboratories.
- [4] "Ultra-Wideband Operation," 47 C.F.R. § 15, Subpart F, Federal Communications Commission.
- [5] IEEE Standard for Low-Rate Wireless Networks, IEEE Std 802.15.4-2020 and Amendment 802.15.4z-2020, IEEE, 2020.
- [6] USB-IF, "USB Type-C Cable and Connector Specification." [Online]. Available: <https://www.usb.org/documents>
- [7] Qorvo, "DWM3000 Data Sheet." [Online]. Available: <https://www.qorvo.com/products/r/ra006953>
- [8] Espressif Systems, "ESP32-C3-MINI-1 Datasheet." [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32-c3-mini-1_datasheet_en.pdf
- [9] Texas Instruments, "TPS6302x Buck-Boost Converter," datasheet. [Online]. Available: <https://www.ti.com/lit/gpn/TPS63021>
- [10] Microchip Technology, "MCP73831/2 Charge Management Controllers." [Online]. Available: <https://www.microchip.com/en-us/product/mcp73831>