

Purrceptron Project Proposal

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Abstract

We propose Purrceptron, a low-cost robotic companion pet that develops a history-dependent relationship with its user through physical interaction. The device uses capacitive touch sensing across its enclosure to classify petting, tapping, holding, and pick-up events, and combines this with inertial sensing to detect handling. These inputs update three internal state variables, mood, energy, and attachment, each with a distinct time constant, which together drive expressive light, sound, servo motion, and differential-drive movement. A real-time clock and battery-backed SRAM allow the pet to maintain its emotional state across shutdown and recharging, so behavior reflects care given over hours and days rather than only the immediate interaction. All sensing, state management, and control run locally on a custom PCB built around an ESP32 microcontroller.

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1. Introduction

1.1 Problem

Loneliness and social isolation are a growing public health concern. Health researchers, including the U.S. Surgeon General, have linked long-term loneliness to a higher risk of heart disease, depression, and earlier death. It also affects communities, since people who feel isolated often have a harder time at work and school.

Spending time with animals is one way people cope with stress, anxiety, and loneliness, and emotional support animals are common for this reason. However, many people cannot own a pet. Housing rules, allergies, cost, travel, and the daily time needed for care all get in the way, and these barriers affect people in many different places and situations.

Current alternatives do not solve this problem well. Virtual pet apps live on a screen, so there is nothing to hold and nothing that exists when the app is closed. Most consumer robot pets follow scripted behaviors that become predictable after a few uses, so users never feel a relationship developing. Robots made for care settings, such as the PARO seal used in dementia care, respond to touch and have shown promising results in small studies. They are expensive and built mainly for institutions, not for individual owners.

Our goal is to build a low-cost robotic companion that responds to touch in a physical way and builds a relationship with its user over time. Its behavior should depend on how it is handled in the moment and on how it has been treated over the past hours and days.

The design also considers safety and welfare. The drive motors stop when the pet is picked up, the enclosure has no small detachable parts, and the battery has protection and a controlled shutdown. The pet has no camera, microphone, or network connection, so no user data leaves the device. We do not present it as a medical or therapy device, and its response to neglect is limited to becoming quiet and withdrawn. It never acts in a way meant to make the user feel guilty. Using one rechargeable battery and a printed enclosure also avoids disposable batteries and reduces waste.

1.2 Solution

Purrceptron is a self-contained, hand-sized robotic pet that reacts to how a person touches it and remembers how it has been treated. It keeps track of three emotional values called mood, energy, and attachment, each on a scale from 0 to 100. These values decide how the pet reacts through four outputs: light, sound, servo motion, and wheeled movement. Mood changes quickly, energy changes over tens of minutes, and attachment changes over days. Because of this, a pet that is handled regularly acts lively and responsive, while a pet that is left alone becomes quiet and slow. All of this is stored on the pet itself, so it does not need a phone, computer, or internet connection, and it keeps its state when it is switched off or recharged.

To sense touch, eight capacitive electrodes connected to an MPR121 controller are placed on the head, back, sides, and underside of the enclosure. An LSM6DSO motion sensor detects when the pet is lifted or shaken. An ESP32-WROOM-32 microcontroller reads both sensors and sorts each event into a pet, tap, hold, or pick-up/shake based on which electrodes activate and how the contact moves over time. Each event changes the emotional values by a small, limited amount, and between events the values slowly drift back toward a baseline. The working state is kept in the backup memory of a DS3232 real-time clock and is saved to flash memory at regular intervals, after major changes, and at shutdown. When the pet turns on, it reads the clock, finds how long it was off, and applies the drift in one step using $S = S_{Base} + (S_0 - S_{Base})e^{(-\frac{dt}{\tau})}$, where S_0 is the saved value, S_{Base} is the baseline, dt is the time off, and τ is the time constant for that value. A soft power button and a battery voltage check make sure the state is saved before power is cut. The pet responds with an LED matrix that shows animated eyes, a MAX98357A amplifier and speaker that play chirps and tones, two SG90 servos that move the head and tail, and two N20 gearmotors with encoders. The gearmotors are driven by a DRV8833 motor driver and work with a ball caster so the pet can turn toward a touch and make short moves. The encoders let the ESP32 control speed and turning angle, and the motors are disabled when the pet is picked up. A single 3.7 V lithium polymer battery powers the system through a BQ24074 charger and a TPS63020 converter that provides the 3.3 V logic supply, while the motors, servos, and amplifier run directly from the battery. All of the electronics are on one custom PCB inside a 3D-printed enclosure.

1.3 Visual Aid

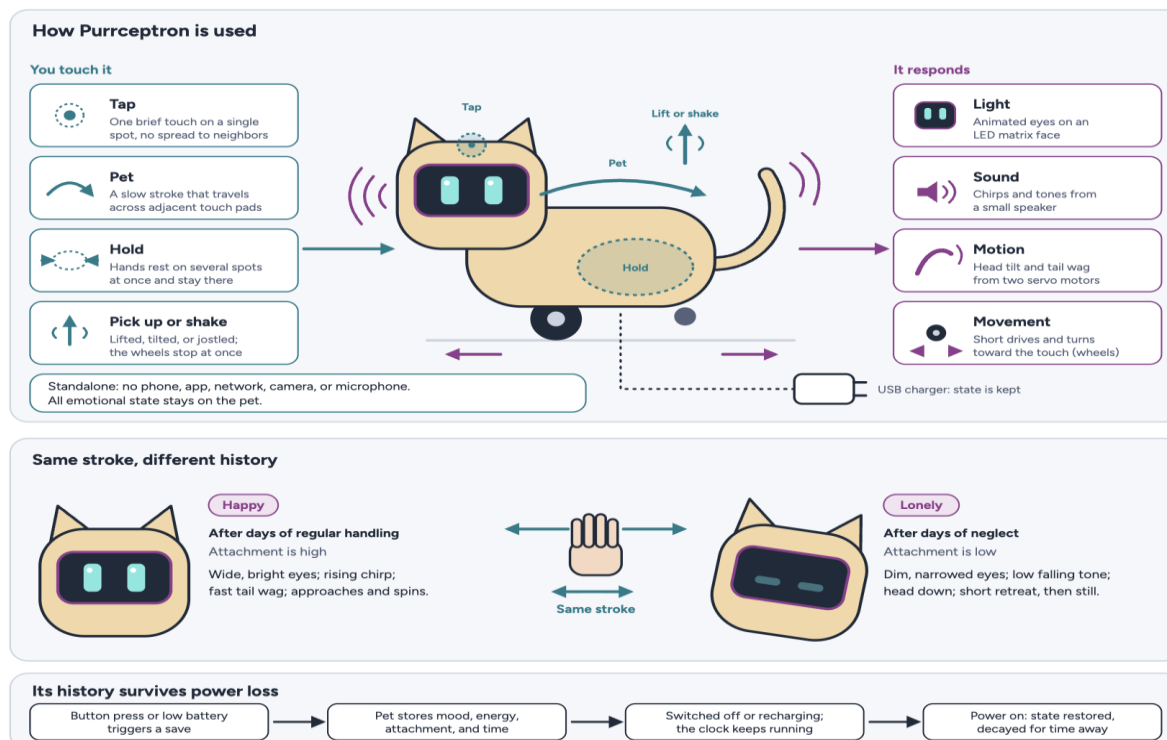


Figure 1. Purrceptron in use. A person pets, taps, holds, or picks up the pet, and it answers with light, sound, motion, and movement. The pet's emotional state is saved and restored across power-off. The pet works entirely on its own, with no phone, app, or network.

1.4 High-level Requirements

- Purrceptron must correctly classify pet, tap, hold, and pick-up/shake interactions at least 90% of the time over at least 30 trials per interaction type, and it must give its first light or sound response within 100 ms of the start of a touch. All classification must run on the onboard microcontroller.
- After being powered off for 30 minutes to 24 hours, the pet must restore its mood and energy values to within 5% of the calculated expected values. This must hold for both a button-press shutdown and a simulated dead battery, with no corrupted or reset state in at least 10 trials of each.
- In a blind test, observers must correctly identify the pet's displayed state (happy, neutral, or lonely) at least 90% of the time using its light, sound, servo motion, and movement together.

2. Design

2.1 Block Diagram

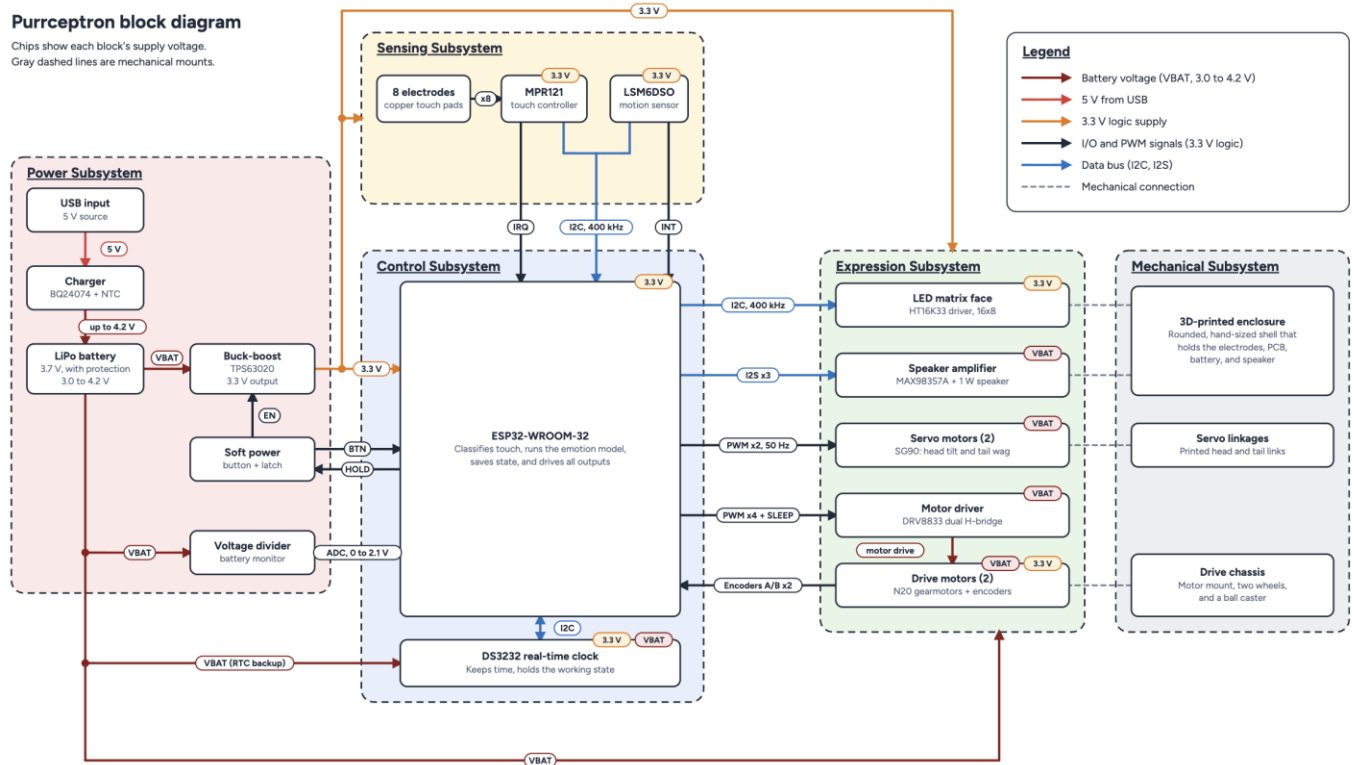


Figure 2: Block diagram of Purrception. The system has five subsystems: power, control, sensing, expression, and mechanical. Line colors show the supply voltage or signal type, and labels on each line show the interface.

2.2 Subsystem Overview

2.2.1 Power Subsystem

The power subsystem lets Purrception run without a cord and gives it a safe way to shut down. A 5 V USB input feeds a BQ24074 charger, which charges a single 3.7 V lithium polymer cell with built-in protection. The cell voltage (VBAT, 3.0 to 4.2 V) goes straight to the servos, the motor driver, and the speaker amplifier. It also feeds the backup pin of the real-time clock. A TPS63020 buck-boost converter turns VBAT into a 3.3 V rail for the microcontroller, sensors, and LED matrix driver. A soft power button and latch control the converter enable line, so the microcontroller can keep power on until it finishes saving. A voltage divider sends a scaled battery voltage to the microcontroller so it can detect a low battery. This subsystem connects to every other subsystem because all of them draw power from it.

2.2.2 Control Subsystem

The control subsystem is the brain of the pet. It has an ESP32-WROOM-32 microcontroller and a DS3232 real-time clock. The ESP32 reads the touch controller and the motion sensor, decides which interaction happened, updates mood, energy, and attachment, and picks an expression. It sends commands to the expression subsystem over I2C, I2S, and PWM, and it reads the wheel encoder signals coming back. It also reads the power button, holds the power latch during shutdown, and reads the battery voltage. The real-time clock shares the I2C bus, keeps time while the pet is off, and holds a working copy of the emotional state in its backup memory.

2.2.3 Sensing Subsystem

The sensing subsystem tells the microcontroller how the pet is being handled. Eight copper electrodes connect to an MPR121 capacitive touch controller, which reports which electrodes are active. An LSM6DSO motion sensor measures acceleration and rotation so the pet can tell when it is lifted, tilted, or shaken. Both chips run from the 3.3 V rail and share the I2C bus with the ESP32. Each chip also has its own interrupt line, so the ESP32 knows right away when something changes. The mechanical subsystem holds the electrodes in the enclosure walls.

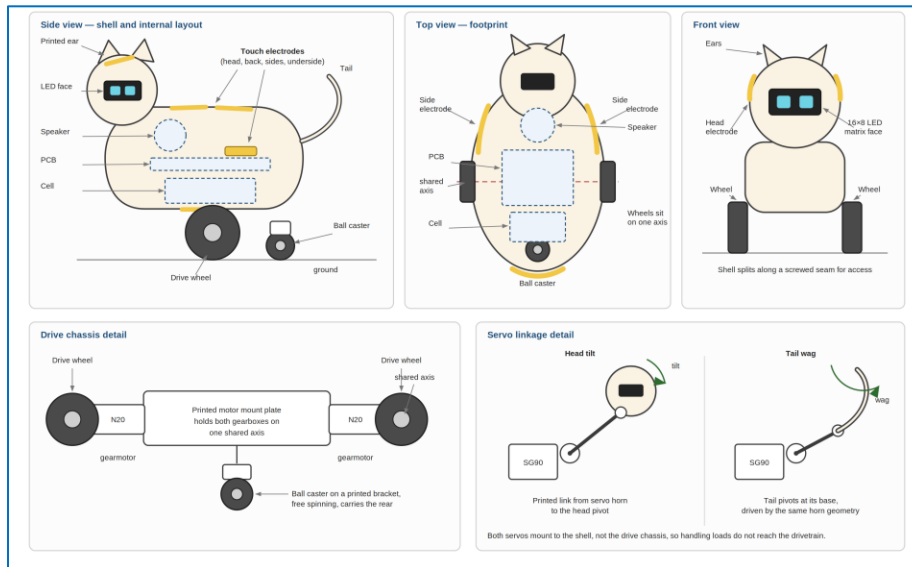
2.2.4 Expression Subsystem

The expression subsystem shows the pet's state through light, sound, servo motion, and movement. An HT16K33 driver runs a 16x8 LED matrix that shows animated eyes. A MAX98357A amplifier plays chirps and tones on a 1 W speaker. Two SG90 servos move the head and tail. A DRV8833 H-bridge drives two N20 gearmotors with encoders, and the encoder signals return to the ESP32 so it can control speed and turning. The LED driver and the encoders run on 3.3 V. The

amplifier, servos, and motor driver run directly from VBAT. The ESP32 controls all four channels, and the mechanical subsystem holds the servos and motors in place.

2.2.5 Mechanical Subsystem

The mechanical subsystem holds everything together and makes the pet safe to handle. The 3D-printed enclosure is a rounded, hand-sized shell that holds the electrodes, the PCB, the battery, and the speaker. The drive chassis carries the two gearmotors, the wheels, and a ball caster. Printed linkages connect the servos to the head and tail. This subsystem has no electrical connections, but it affects the others directly. The wall thickness over the electrodes changes how well touch is sensed, and the alignment of the motors changes how well the pet drives straight.



2.3 Subsystem Requirements

2.3.1 Power Subsystem

Description: The power subsystem supports all three high-level requirements. It supplies every other subsystem. Its low-battery detection and soft power latch give the pet time to save its state before power is lost, which supports state persistence.

Interfaces:

- Input: 5 V $\pm$ 0.25 V from a USB source into the charger.
- VBAT output: 3.0 to 4.2 V to the speaker amplifier, servos, motor driver, and real-time clock backup pin.
- 3.3 V output: 3.3 V $\pm$ 0.1 V to the ESP32, DS3232, MPR121, LSM6DSO, HT16K33, and encoders.
- Battery monitor output: 0.5 x VBAT (1.5 to 2.1 V) to one ESP32 ADC pin.

- Soft power signals: BTN (3.3 V logic, latch to ESP32) and HOLD (3.3 V logic, ESP32 to latch).

Requirements:

- The VBAT rail must supply at least 2.0 A for 100 ms without the terminal voltage dropping below 2.7 V.
- The 3.3 V rail must stay at 3.3 V +/- 0.1 V with up to 300 mA of load while VBAT is anywhere from 2.8 V to 4.2 V.
- The 3.3 V rail ripple must stay under 50 mV peak to peak at 300 mA so it does not disturb the touch sensing or the ADC.
- The battery monitor must use a 0.5 divider ratio with 1% resistors, and the total voltage reading error must stay within +/- 4% after calibration.
- A low-battery save must trigger at a reading of 3.40 V, and the cell protection cutoff must be below 3.0 V so the save always happens first.
- The 3.3 V rail must stay on while HOLD is high and turn off within 50 ms after HOLD goes low. A button press must never cut power directly.
- The total current drawn from the cell while the pet is off must be under 100 uA, and the real-time clock must keep running.
- The charger must stop charging at 4.2 V +/- 1% and must stop if the thermistor reads out of range.
- The subsystem must run the pet for at least 3 hours of intermittent use on one charge.

2.3.2 Control Subsystem

Description: The control subsystem supports all three high-level requirements. It classifies touch and starts the response within 100 ms. It runs the emotional state model and restores the state after power loss. It also chooses the expression for each state.

Interfaces:

- I2C at 400 kHz and 3.3 V, shared by the MPR121 (address 0x5A), LSM6DSO (0x6A), DS3232 (0x68), and HT16K33 (0x70).
- Two active-low interrupt inputs at 3.3 V logic: MPR121 IRQ and LSM6DSO INT.
- I2S output to the MAX98357A at a 16 kHz sample rate and 16 bits.
- Six PWM outputs: two servo signals at 50 Hz (1 to 2 ms pulses) and four DRV8833 inputs at 20 kHz. One extra output controls the DRV8833 SLEEP pin.
- Two quadrature encoder inputs, up to 10 kHz per channel.
- One ADC input (0 to 2.1 V) for battery voltage, one button input (BTN), and one power hold output (HOLD).

Requirements:

- All touch classification must run on the ESP32. A classification decision must be made within 60 ms of touch onset, and the first output must start within 20 ms after that.

- The firmware must read the MPR121 at least every 20 ms and the LSM6DSO at 100 Hz or faster.
- Each classified event must change the state by a limited amount, and mood, energy, and attachment must always stay between 0 and 100.
- At power-up, the calculated decay must be within 1% of the expected value.
- The state block (mood, energy, attachment, timestamp, and a check value) must be saved in under 200 ms. At start-up, a failed check value must cause the firmware to fall back to the last good checkpoint in flash.
- Flash checkpoints must happen no more than once every 10 minutes, plus once on major state changes and once at shutdown.
- When a low battery is detected, the motors must be disabled within 10 ms, and then the state must be saved.
- When a pick-up is detected, the motor PWM outputs must go to zero and SLEEP must go low within 50 ms.
- If the clock oscillator stop flag is set at start-up, the firmware must restore the last checkpoint without applying decay and then reset the clock.
- The motor speed and turn control loops must run at 100 Hz or faster.

2.3.3 Sensing Subsystem

Description: The sensing subsystem gives the pet all of its input. It supports the touch classification requirement, and it provides the pick-up signal that keeps the wheels from turning while the pet is held.

Interfaces:

- Supply: 3.3 V +/- 0.1 V, with a total draw under 5 mA.
- MPR121: I2C at 400 kHz (address 0x5A) with an active-low IRQ output, connected to the 8 electrodes.
- LSM6DSO: I2C at 400 kHz (address 0x6A) with an active-low INT output. The acceleration range is +/- 4 g at 104 Hz or faster.

Requirements:

- The pet must detect touch at all 8 test points, with fewer than 5% missed touches over 5 trials per point.
- The sampling rate must be fast enough to tell apart two neighboring electrodes that activate 50 ms apart, so a stroke is not mistaken for a tap.
- The pet must register no more than one false touch during a 5-minute test with the motors, servos, and speaker all running.
- The motion sensor must raise its interrupt within 100 ms of a lift in at least 19 of 20 trials.
- The electrode traces must have a guard ring, and the analog and power grounds must join at a single point.

- Sensor reads must fail or drop out no more than 5% of the time over a 10-minute test with the motors running.

2.3.4 Expression Subsystem

Description: The expression subsystem supports the distinguishable expression requirement and the 100 ms response time. It also handles all movement.

Interfaces:

- LED matrix driver: HT16K33 on the 3.3 V rail, I2C at 400 kHz (address 0x70).
- Speaker amplifier: MAX98357A with a 3.3 V I2S input and a VBAT supply, driving 1 W into 4 ohms.
- Servos: 3.3 V PWM signals at 50 Hz with a VBAT supply, drawing up to 0.3 A each while moving.
- Motor driver: DRV8833 with 3.3 V PWM inputs at 20 kHz and a VBAT supply. Each motor is limited to 0.3 A by a software soft start.
- Encoders: 3.3 V supply, two channels per motor, sent back to the ESP32.

Requirements:

- The pet must have a different combination of eye animation, tone pattern, servo pattern, and movement pattern for each of the happy, neutral, and lonely states. Observers must identify the state at least 90% of the time.
- The LED matrix must show at least 3 different eye shapes and update at least 10 times per second.
- The speaker must play tones from 200 Hz to 4 kHz at 60 dB or louder, measured 30 cm from the pet.
- The servos must reach a commanded position within +/- 5 degrees for any VBAT from 3.3 V to 4.2 V.
- With encoder feedback, the pet must drive a commanded 1 m path with less than 10 cm of side drift, and turn 90 degrees to within +/- 10 degrees, over 20 trials each.
- The travel speed must be between 0.05 and 0.2 m/s, and firmware must limit each behavior to 50 cm of travel from the start point.
- The drive motors must stop within 200 ms of a detected pick-up, with no case of a wheel still turning.
- Each motor must have a snubber capacitor across its terminals and a ferrite bead on each lead. The motor driver must have at least 100 uF of local bulk capacitance.
- With all four channels running at once, the total peak current from VBAT must stay at or below 1.7 A.

2.3.5 Mechanical Subsystem

Description: The mechanical subsystem supports the touch classification requirement by holding the electrodes at a distance where touch can still be sensed. It also holds the drive parts in alignment and keeps the pet safe to pick up.

Interfaces:

- The enclosure holds the 8 electrodes, the PCB, the battery, and the speaker.
- The drive chassis holds two gearmotors on one shared axis, two wheels, and a ball caster.
- Printed linkages connect each SG90 servo horn to the head or tail.

Requirements:

- The enclosure wall over each electrode must be no thicker than 2 mm at first. The final thickness will be set by testing so all touch test points still pass.
- The two motor axes must line up within 1 mm, and the two wheels must sit on one axis.
- The ball caster must keep all three ground contacts down and must not let the pet tip during acceleration of up to 0.5 m/s^2 .
- The pet must weigh no more than 400 g and fit inside a 15 cm x 12 cm x 10 cm box.
- All pinch points at the servo linkages and wheels must be enclosed so openings are under 5 mm. The pet must have no detachable part small enough to fit in a 3 cm wide tube.
- The battery, PCB, and speaker must be mounted on standoffs or mounts that do not connect to the drive assembly or servo linkages, so normal handling does not stress solder joints or wires.

2.4 Tolerance Analysis

The biggest risk in this design is the battery voltage dropping too low when the motors, servos, and speaker all draw current at once. If the voltage falls below what the parts need before the pet finishes saving its state, the state could be lost and the state persistence requirement would fail. This section checks whether the planned low-battery trigger of 3.40 V leaves enough margin. All values are working estimates and will be replaced with measurements from our power budget table.

Assumptions:

- Cell capacity: 1000 mAh
- Total source resistance: 0.25 ohm (cell, protection circuit, and wiring)
- Motor winding resistance: 7 ohm, plus 0.4 ohm for the H-bridge
- Lowest supply voltage for the VBAT parts: 2.7 V, set by the DRV8833 (to be confirmed in its datasheet)
- Battery voltage reading error: +/- 4% total (+/- 1% from the divider resistors and +/- 3% from the ADC after calibration)

Step 1: Peak current and voltage sag

- Two motors, soft start limited to 0.30 A each: 0.60 A
- Two servos moving under load, 0.30 A each: 0.60 A
- Speaker at 1 W, 85% efficiency, 3.4 V: $\frac{1}{(0.85 \cdot 3.4)} = 0.35A$
- Logic rail at 0.15 A and 3.3 V, 90% converter efficiency: $\frac{(3.3 \cdot 0.15)}{(0.9 \cdot 3.4)} = 0.16A$
- Total: 1.71 A, which gives a sag of $1.71 \cdot 0.25 = 0.43V$

Without the soft start, each motor could draw $\frac{3.5}{(7+0.4)} = 0.47A$ when starting. The total would be 2.05 A and the sag would be 0.51 V.

Step 2: Margin at the trigger

The firmware saves when the reading is 3.40 V. With a +/- 4% error, the real cell voltage is between $\frac{3.4}{1.04} = 3.27V$ and $\frac{3.4}{0.96} = 3.54V$. In the worst case, the cell is at 3.27 V and a full peak load hits at that moment:

- With soft start: $3.27 - 0.43 = 2.84V$, which is 0.14 V above the 2.7 V limit
- Without soft start: $3.27 - 0.51 = 2.76V$, which is only 0.06 V above the limit

The 0.06 V margin is too small once real parts vary, so the soft start is required.

Step 3: Energy for the save

When the trigger fires, the motors turn off first and the load drops to about 0.16 A. The save takes at most 200 ms, so it uses $0.16A \cdot 0.2s = 0.032 C$, or about 0.009 mAh. We assume at least 3% of the cell (30 mAh) remains between 3.27 V and the protection cutoff. That is more than 3000 times what the save needs.

Step 4: Cost to battery life

If the trigger fires early (real voltage 3.54 V), we assume about 80% of the rated capacity is usable, or 800 mAh. The estimated average current is:

- Logic rail: $(0.125 A \times 3.3 V) / (0.9 \times 3.7 V) = 0.124 A$
- Motors, moving 10% of the time at 0.12 A each: 0.024 A
- Servos, moving 15% of the time at 0.15 A each: 0.045 A
- Speaker, playing 10% of the time at 0.20 A: 0.020 A
- Total: about 0.21 A

Three hours at 0.21 A needs 640 mAh. The 800 mAh available in the worst case gives a 25% margin.

Conclusion: With a soft start on the motors, a 3.40 V trigger, and a cell of at least 1000 mAh, the pet can finish saving before the voltage gets too low, and it still meets the 3-hour battery life target. If

our measurements show a margin below 0.1 V in Step 2, we will raise the trigger to 3.50 V or stop the servos and motors from running at the same time.

3. Ethics, Safety, and Societal Impact

3.1 Ethical Issues

We reviewed Purrception against the IEEE Code of Ethics and the ACM Code of Ethics. IEEE Code I.1 asks us to put public safety, health, and welfare first and to protect privacy, and I.5 asks for honest, realistic claims. ACM 1.2 and 2.5 ask us to avoid harm and to evaluate a system's risks carefully. Because Purrception looks like an animal and is aimed at people who feel lonely or anxious, we will call it a companion toy, not a therapy device. It has no camera, microphone, or network connection, and it stores only three emotional values and a timestamp, which follows ACM 1.6 on privacy. Neglect only makes the pet quiet and withdrawn, never guilt-inducing, and it recovers with regular contact, which follows ACM 1.1 on psychological harm. We will also test touch sensing with volunteers of different hand sizes, skin conditions, and touch strengths, and the pet uses four output channels so users with limited sight or hearing can still read its state (IEEE II.7, ACM 1.4).

To avoid ethical breaches, we will keep a test log with every trial, including failed ones, and report results as measured. We will credit all outside code, libraries, and reference designs and follow their licenses (IEEE I.5, ACM 1.5). Volunteers in our tests will give permission and stay anonymous, and we will ask course staff whether the blind test needs review. The team will check the user guide and demo script so no claim goes beyond what the pet does. Any member can stop work over a safety concern and report it to course staff right away.

3.2 Safety

During development, the lithium polymer battery is the biggest hazard because it can catch fire if it is punctured, shorted, or overcharged. We will follow the ECE 445 battery guidelines and finish the extra battery safety training before charging any cell. We will use a protected cell, charge it only in the lab while we can watch it, and inspect it for swelling. For soldering and shop work, we have already complete the lab safety training and will get guidance from the machine shop staff. The highest voltage in the system is 5 V from USB, and the touch electrodes sit behind the enclosure wall and do not run current through the user. We will still confirm with course staff that the ECE 445 human-subject current guideline does not apply.

During normal use, the main risks are falls, pinching, swallowing small parts, and battery damage. The base design has no edge sensors, so we limit each movement to 50 cm and will

program the pet to stop if the motion sensor detects a fall or tip. The motors also stop within 200 ms of a pick-up, and the pinch points are enclosed. The pet has no small detachable parts, and the cell is mounted inside a closed, screwed-shut enclosure. The cell protection and charger safety features work without firmware, so changed firmware cannot overcharge or over-discharge the cell. Since the pet has no camera or microphone and we will include no wireless code, it cannot be used to watch people. A label will say to charge it only with a USB 5 V adapter and not to open it.

3.3 Societal, Economic, Environmental, and Global Impact

Loneliness affects both health and communities. Purrceptron gives people who cannot keep a real animal, such as those in housing that does not allow pets or those with allergies, a companion they can touch. The main risk is that someone might use it in place of human contact, so the user guide will say it is not a replacement for people. We use common, low-cost parts and a 3D-printed shell, so the pet can be built and repaired by ordinary people. It has no app, no cloud service, and no subscription, so there are no ongoing fees. This is an advantage over adaptive care robots, which cost much more and are built mainly for institutions.

Electronics, plastic, and lithium batteries all create waste. We use one rechargeable cell instead of disposable batteries and screws instead of glue so the pet can be repaired. The printed shell can be reprinted, and the cell must go to a battery recycling point at the end of its life. Because the pet's behavior changes with how it is treated, we hope people keep using it longer, which helps avoid early disposal. Globally, the pet charges from any standard 5 V USB adapter and has no mains voltage inside. It uses touch, light, sound, and motion instead of speech or text, so it has no language barrier. Attitudes toward pets and animal-like objects differ across cultures, so the shell can be reshaped or recolored. Selling it abroad would need extra steps, such as CE marking and RoHS compliance in Europe.