

Rapid Adaptation Rover

Learned Dynamics Compensation for a
Differential Drive Robot

Project Proposal

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1 Introduction

1.1 Problem and justification

A differential-drive rover can respond differently to the same motor commands when its payload, incline, or mechanical resistance changes. Added mass alters acceleration; an incline adds gravity load; drag increases motor effort. These effects matter during transients even when a fixed-gain controller eventually restores steady speed.

We will investigate whether recent onboard measurements can reveal useful information about changing dynamics and improve motion tracking. The same rover will be evaluated using tuned conventional control, a learned policy with a fixed dynamics representation, and that policy with history-based adaptation.

The intended application is small indoor transport robots whose loads and travel conditions vary. This project demonstrates short-duration speed and turning control within a measured operating envelope. Global position tracking, autonomous navigation, arbitrary terrain traversal, and deployment around untrained users are outside its scope.

1.2 Proposed solution

We will build a four-wheel-supported rover with two driven wheels, two passive casters, a custom STM32 control and sensing PCB, and a Raspberry Pi 4. A compact network will infer a dynamics representation from recent onboard sensor and applied-command history. This approach is inspired by rapid motor adaptation [1]. A downward-facing optical-flow sensor will provide an evaluation-only surface-motion reference; the existing IMU will measure yaw rate.

Rapid Adaptation Rover: intended use and test context

Small indoor transport platform; controlled payload, incline and drag trials. Views are schematic.

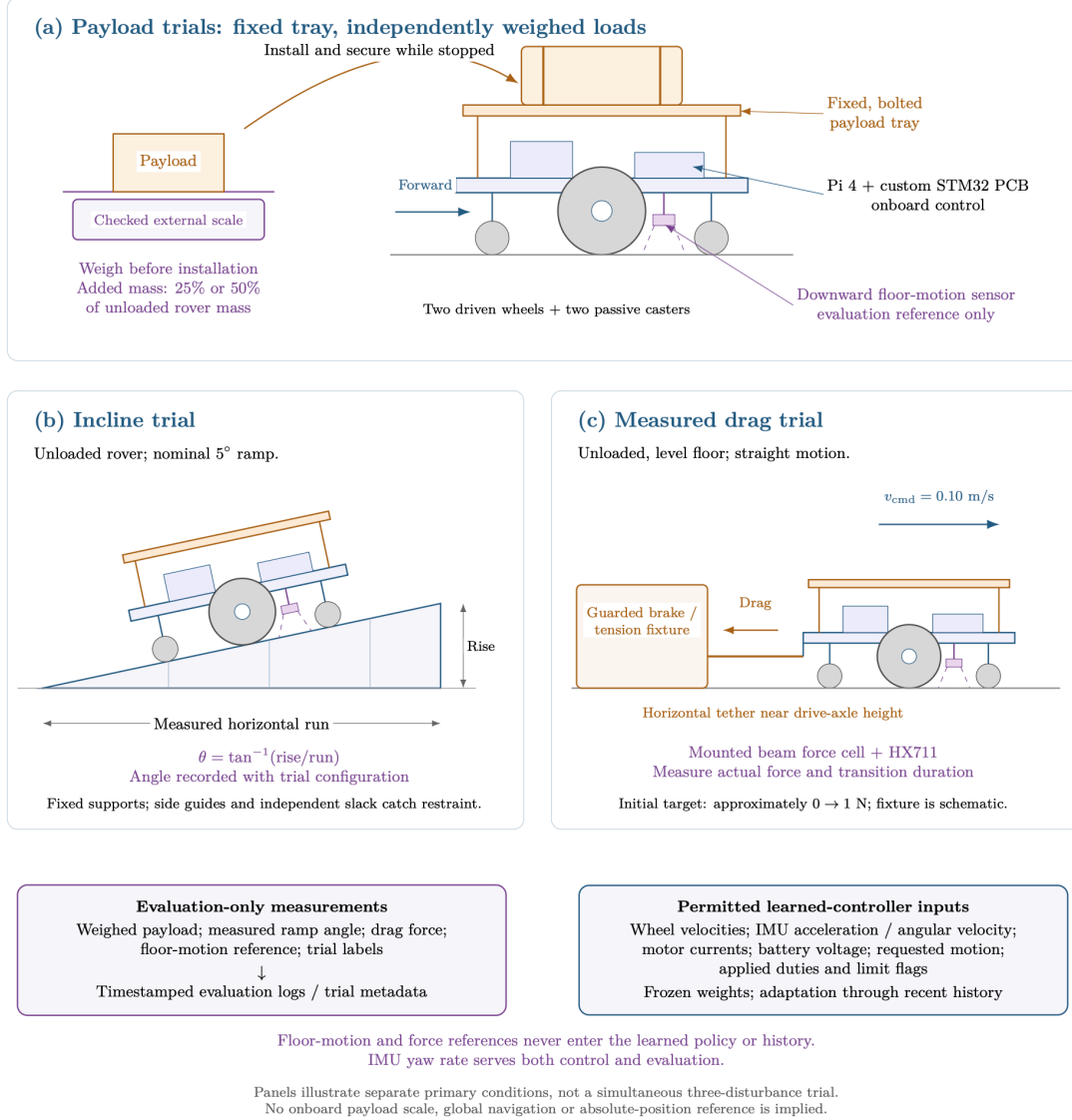


Figure 1. Intended use of the Rapid Adaptation Rover. Payload, incline and drag are independently quantified. A fixed tray carries secured payloads, a supported ramp provides a repeatable incline, and a guarded tether fixture applies measured drag. Floor-motion and force reference data are excluded from the learned controller.

The demonstration retains payload increases of 25–50% of unloaded rover mass, a simple ramp, and measured drag. Payloads are weighed before installation. Frozen network weights are used throughout final tests; adaptation occurs through the changing history-derived representation.

1.3 High level requirements

The following are proposed acceptance requirements for the defined test set, not measured results. Initial numeric targets will be checked during characterization and frozen before final evaluation. Any revision will be documented before testing; a weaker result will not be reported as meeting an earlier target.

- **HL1** In at least four of five valid trials for each primary condition in Table 1, the adaptive rover shall achieve forward-speed RMSE ≤ 0.02 m/s and yaw-rate RMSE ≤ 0.10 rad/s. After a measured in-motion drag change, it shall recover to both error bands within an initial target of 1.5 s and remain there for 0.5 s in at least four of five trials. Verification: Use calibrated floor-motion and IMU measurements, measured force onset, and the common analysis windows in Section 2.8. A separate nominal turning test shall meet the yaw-rate threshold.
- **HL2** With frozen weights and no disturbance labels or evaluation-only inputs, the adaptive policy shall reduce mean forward-speed RMSE by at least 10% relative to the fixed-latent policy in the predefined primary drag condition. Verification: Compare five matched trial pairs with identical profiles and limits, and apply the measurement-resolution rule in Section 2.8. Report both learned modes and tuned PI for every condition. Reductions of 25% versus fixed-latent and 10% versus PI across all disturbed conditions remain research targets, rather than required wins in every comparison.
- **HL3** The integrated rover shall sustain a 50 Hz onboard policy loop for ten minutes with zero missed 20 ms deadlines while acquiring control observations and logging telemetry at 100 Hz. After loss of valid commands, both drivers shall disable within 101 ms of the last valid command. A latching hardware emergency stop shall disable drive independently of Pi software. Verification: Measure complete-loop timing and packet continuity; test communication loss and hardware stop with restrained wheels.

Table 1. Proposed physical test envelope and measurement targets.

Condition	Magnitude and command	Measurement and verification
Nominal reference	Unloaded, level dry floor; straight speed profile; turning tested separately	Floor-motion reference and calibrated IMU; voltage and temperature recorded
Primary payload	Added mass = 25% and 50% of measured unloaded mass; fixed central location	External scale before loading; initial uncertainty target ± 0.05 kg
Primary incline	Unloaded rover, nominal 5° ramp; 0.10 m/s uphill	Direct angle measurement target $\pm 0.5^\circ$
Primary drag	Unloaded, level floor; measured change from approximately 0 to 1 N at 0.10 m/s	One force cell and HX711; initial error target ± 0.10 N
Additional combination	50% payload + 5° incline at 0.10 m/s; excluded from physical tuning	Same measurements; report separately without an extra pass threshold

Forward commands will remain within 0–0.20 m/s and yaw-rate commands within ± 1 rad/s, jointly limited by measured wheel-speed and current capability. Primary disturbance tests use straight motion; nominal turning is tested separately. The combination trial is additional evaluation, not an extra HL1 or HL2 pass condition.

2 Design

2.1 System architecture and interfaces

Figure 2 separates the real-time PCB, learned controller, actuation, power, and evaluation paths. The PCB uses STM32G431CBT6 [2], DRV8874 drivers [3], INA240A1 amplifiers [4], SN74LVC14A input conditioning [5], and an ICM-42688-P IMU [6]. Component selections are design inputs; subsystem acceptance requirements follow in Sections 2.2–2.8.

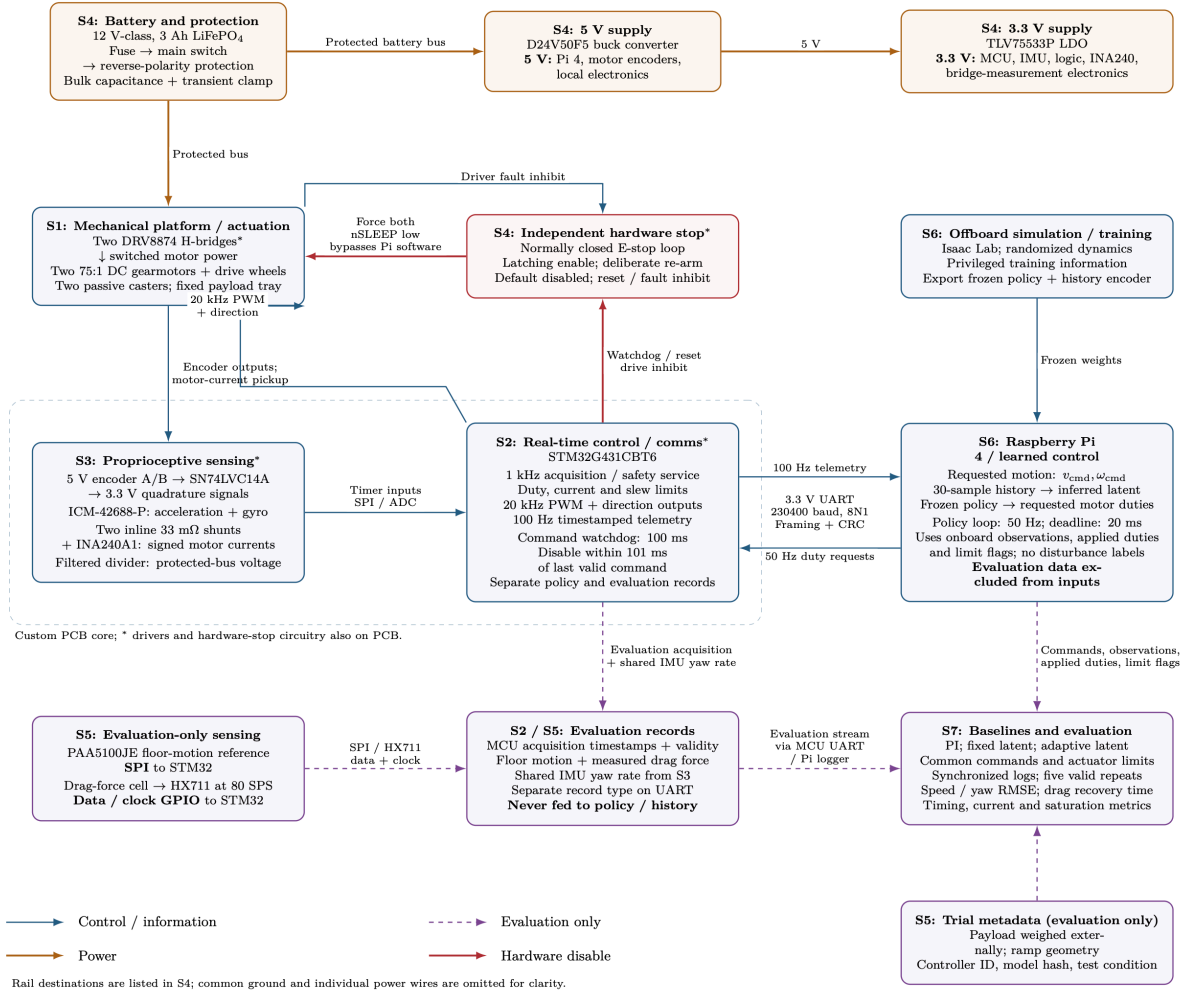


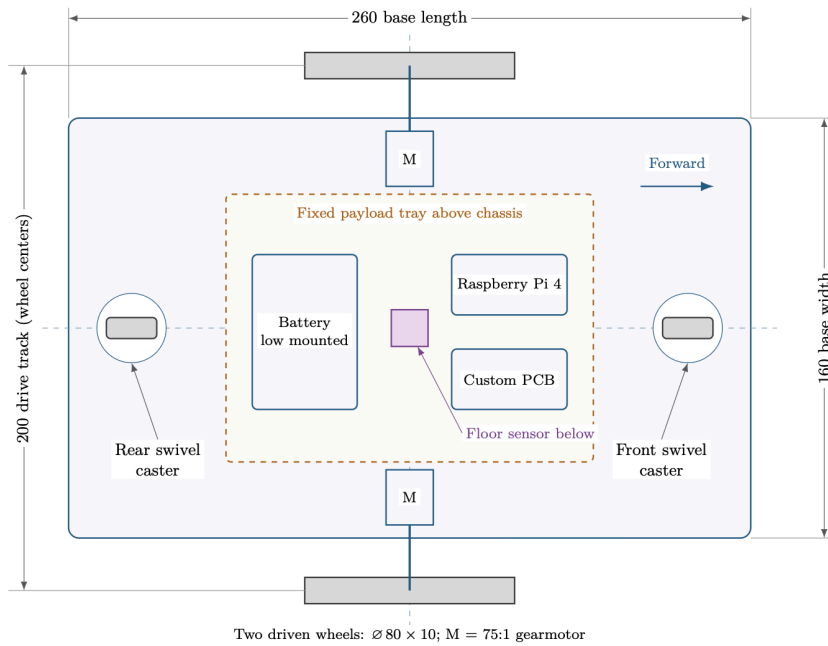
Figure 2. Electrical and information architecture of the Rapid Adaptation Rover. The hardware stop bypasses Pi control. Floor-motion and drag-force data enter evaluation logs only; IMU data serve both control and evaluation. Subsystem IDs S1–S7 match Table 3 of the proposal

2.2 Mechanical platform and actuation

Two Pololu #4866 75:1 MP 12 V gearmotors provide differential drive. Their 4 mm D shafts match the 4 mm inserts of the #3690 80×10 mm multi-hub wheel pair; #2676 brackets mount the 25D motors to the baseplate [7] [8] [9]. Front and rear swivel casters complete the four-wheel support. Figure 3 gives an initial layout; dimensions are proposed packaging values, not released manufacturing dimensions.

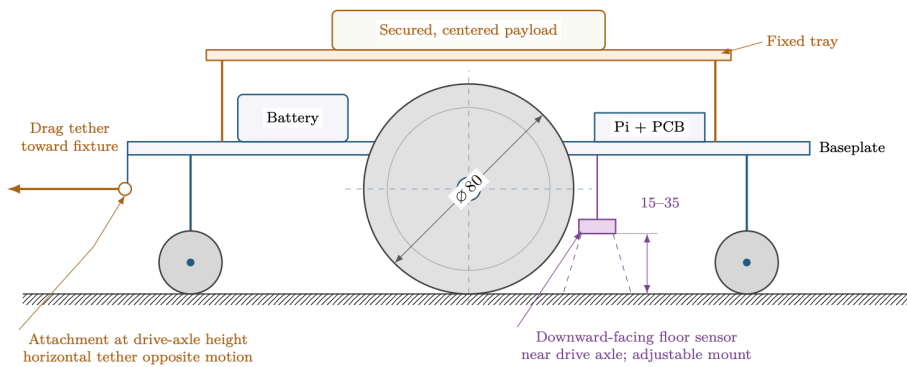
(a) Top view

Preliminary component arrangement; front is to the right.



(b) Side view

Schematic, not to scale; opposite drive wheel is hidden in this projection.



Two drive-wheel contacts on the transverse centerline; passive caster contacts fore and aft.

Figure 3: Mechanical concept with top and side views. The proposed base is 260×160 mm, with a 200 mm drive track, two 80×10 mm driven wheels, and two passive casters. A fixed tray holds the secured payload; the battery is mounted low. Dimensions are in millimeters and are preliminary packaging values, not released manufacturing dimensions. Side view is schematic and not to scale.

A rigid tray will bolt directly to the chassis. Payloads will be weighed on a checked laboratory or household scale before installation and secured at a marked central location. There is no onboard payload-weighing mechanism. The floor-motion sensor will mount near the drive axle with adjustable height and protection against surface contact. A rigid ramp with fixed supports provides a repeatable incline; no powered adjustment is required.

M1 The platform shall retain its battery and payload throughout the test motions while keeping both drive wheels loaded. *Verification:* Inspect fasteners and restraints; measure drive-wheel load share; traverse the ramp and transitions at low speed. Adjust or compliantly mount the casters to avoid chassis rocking or unloading the drive wheels.

M2 The drive system shall deliver both straight and turning motion without sustained saturation in the accepted disturbance envelope. *Verification:* Run the torque, traction, and thermal characterization described in Section 2.10; check wheel slip, current, and speed before learned trials.

2.3 Real time control and proprioceptive sensing

The STM32 will generate separate 20 kHz PWM signals and direction commands for the two H-bridges. A 1 kHz task will update wheel estimates, service acquisition, monitor faults, and apply current, duty, and slew limits. Hardware current regulation will initially target approximately 1.2 A peak per motor; a lower sustained-current limit and stall timeout will be established by thermal testing. The learned policy will request normalized duty directly. The PI baseline will use the same command-limiting layer, rather than an extra PI loop being silently inserted beneath the learned controller.

The two motor encoders will operate at 5 V. All four quadrature outputs will pass through a 3.3 V SN74LVC14A before STM32 timer capture; its inputs tolerate 5 V logic at that supply [5]. Inverting both channels preserves quadrature phase order; channel order and direction sign will be checked on each installed motor. The IMU will use 3.3 V power and SPI. It measures acceleration and angular velocity, not absolute heading [6].

Each motor lead will include a Kelvin-connected 33 m Ω shunt and an INA240A1 channel. This inline placement measures signed winding current, including recirculation, rather than assuming battery current equals motor current. One amplifier reference pin will connect to the 3.3 V supply and the other to ground, following the data-sheet midsupply configuration. Zero-current calibration will remove the measured initial zero offset. PWM-synchronized acquisition, input filtering consistent with the amplifier data sheet, and calibration will reduce switching artifacts. A filtered divider will measure protected-bus voltage; divider ratios and clamps will keep the ADC input within its range under specified bus transients. Section 2.9 analyzes current-channel feasibility.

Table 2. Proposed embedded timing and communication design.

Function	Design value	Implementation check
Motor PWM / service	20 kHz / 1 kHz	Timer outputs and worst-case service latency measured
Telemetry / policy	100 Hz / 50 Hz	MCU timestamps, sequence numbers, complete loop timing
UART electrical link	3.3 V, full duplex, 230400 baud, 8N1	Framed length, CRC, monotonic sequence; reject stale packets
History window	30 policy samples = 0.60 s	Uniform time alignment; validity mask or safe startup fill
Encoder resolution	$48 \times 74.83 \approx 3592$ counts per wheel revolution	48 CPR already counts both edges on both channels

A maximum 128-byte telemetry packet at 100 Hz consumes 128 kbit/s with 8N1 framing, below the 230.4 kbit/s link rate. Encoder velocity will use a filtered count window or edge timing; a 1 ms difference alone is too coarse at low speed. Sensor age, applied duty, requested duty, and limit flags will be logged together.

C1 Control and sensing shall execute concurrently without corrupting timestamps, direction, or applied-command reporting. *Verification:* Use oscilloscope timing, known wheel rotations, a known current load, and packet sequence checks under maximum compute and motor activity.

C2 Only calibrated onboard observations and permitted commands shall enter the deployed history and policy inputs. *Verification:* Audit the serialized observation schema and recorded tensors; disconnect the reference-measurement stream and confirm continued operation.

2.4 Power distribution and independent safety

A Bioenno BLF-1203AB 12 V-class, 3 Ah LiFePO₄ pack will supply the rover through a fuse, main switch, and reverse-polarity protection. The manufacturer lists a 7 A continuous discharge limit; the matched BPC-1502DC charger operates at 14.6 V [10]. The motor bus must therefore tolerate the fully charged pack and switching transients. The pack protection is a last-resort safeguard, not the control system's current limiter.

A Pololu D24V50F5 #2851 will generate 5 V for the Pi, encoders, and local electronics [11]. A TLV75533P will generate 3.3 V for the MCU, IMU, logic, current amplifiers, and bridge-measurement electronics [12]. Raspberry Pi guidance calls for a 5 V, 3 A supply for Pi 4 [13]; regulator capacity alone does not prove adequate voltage at the board. Short power wiring, grounding, cooling, and simultaneous processor/motor loading will be verified. The Pi will receive 5 V only through a protected, correctly wired power input, with no competing USB power source.

The preliminary 3.3 V load budget is 150 mA, giving approximately $(5-3.3) \times 0.15 = 0.255$ W LDO dissipation. The buck converter will be qualified at the installed ambient temperature. As a conservative supply estimate, a 3.2 A 5 V load at 85% efficiency and an 11 V battery consumes approximately 1.71 A from the pack. Adding two 1.2 A motor-channel peaks gives 4.11 A, below the pack's listed 7 A continuous ceiling. This arithmetic is a sizing estimate, not a substitute for startup-current, fuse, wire, connector, or regulator thermal testing.

Firmware will cap duty magnitude at $\min(1, 12 \text{ V}/V_{\text{bus}})$, in addition to peak current, sustained current, and command slew limits. This limits approximate average applied voltage, not instantaneous winding voltage or regenerative energy. Bulk capacitance and a suitably rated transient-clamp or energy-dissipation path will keep bus excursions within every connected component's rating; reverse-polarity circuitry must not leave regenerative energy without a safe path. Clamp selection will follow measured braking energy and pulse-current checks.

A normally closed emergency-stop loop and latching hardware enable circuit will force both DRV8874 nSLEEP pins low independently of the Pi. Broken stop-loop wiring, MCU reset, invalid startup state, or driver faults will inhibit drive. Pull-downs will establish the disabled state before firmware starts. Clearing a fault or releasing the button will require deliberate re-arming; it will not automatically resume motion. The MCU command watchdog will expire at 100 ms, with a maximum additional 1 ms service interval. A separate MCU watchdog protects against firmware lockup.

P1 Power distribution shall maintain valid logic operation during motor startup, reversal, and simultaneous compute load. *Verification:* Probe supply minima and bus maxima; record brownout/reset flags and temperatures; verify fuse coordination and component ratings before unrestricted driving.

P2 Safety shutdown shall remain effective when Pi software hangs or communication fails, and restart shall require deliberate action. *Verification:* Test lost UART traffic, stale/CRC-failed packets, MCU reset, driver fault, broken stop wiring, and emergency-stop operation. Observe both driver enables and wheel motion.

Driver disable removes commanded torque; it does not guarantee immediate stopping or prevent downhill rolling. Ramp tests will therefore use side guides and an independent slack catch restraint that does not load the rover during valid data collection.

2.5 Disturbance and onboard motion measurements

Wheel rotation does not establish ground speed during slip. A downward-facing PAA5100JE near optical-flow breakout is the initial evaluation sensor candidate. Its documented working height is 15–35 mm and it communicates over SPI [14]. The MCU will timestamp displacement readings and maintain a separate evaluation record. Calibration will convert displacement to forward surface velocity at the installed height; vendor specifications alone do not establish the required accuracy.

Payload mass will be measured at rest on a scale checked with reference masses, with a proposed uncertainty of ± 0.05 kg. The unloaded mass includes the fixed tray and installed electronics. Added payloads will equal 25% and 50% of that mass. Ramp angle will be established from measured rise and horizontal run, with a proposed uncertainty of $\pm 0.5^\circ$. These measurements are recorded with the trial configuration and never supplied to the controller.

One low-cost force cell and HX711 board will measure drag. A roughly 500 g beam cell is a candidate for the 0–2 N measurement range, subject to calibration and overload margin [15]. It must be mounted as a bending beam with force applied along its specified sensing direction; it is not assumed to be a ready-made inline tension sensor. The HX711 supports 10 or 80 samples/s [16]; the planned 80 samples/s mode uses data/clock GPIO and acquisition timestamps. Logic levels, excitation, conversion delay, and force-step response will be verified. Repeated entries in the 100 Hz log retain their acquisition times.

A guarded brake or tension fixture behind the rover will apply drag through a lightweight tether near axle height. The initial condition is a change from approximately zero to 1 N at 0.10 m/s. Actual force and transition duration will be logged; a nominal brake setting is not the disturbance measurement. The line remains approximately horizontal and opposite motion. A straight lane limits tether complications. No sub-0.10 s force transition is promised. Mechanical snags or catch-restraint contact are fixture failures; controller saturation and failed recovery remain valid outcomes.

The floor sensor will be calibrated on the chosen textured floor and ramp surfaces using known distances, independent travel times, and repeated traverses. Mount height, tilt, rotation, and sensor offset from the rover reference point will be checked. Measurement windows begin after the rover is fully on the ramp; entry and exit are safety checks outside the primary tracking window. The calibrated IMU supplies body yaw rate for both control and evaluation, so it is not an independent heading reference. Gyro bias and scale will be checked at rest and against known angle/time motion. Absolute heading and global position are not acceptance metrics.

E1 Disturbances shall be independently quantified without entering policy or history inputs. Verification: Check scale readings, force calibration, force hysteresis, and ramp geometry; inspect evaluation records and the policy input schema. The force channel shall resolve the selected drag levels, with an initial calibrated error target of ± 0.10 N over 0–2 N.

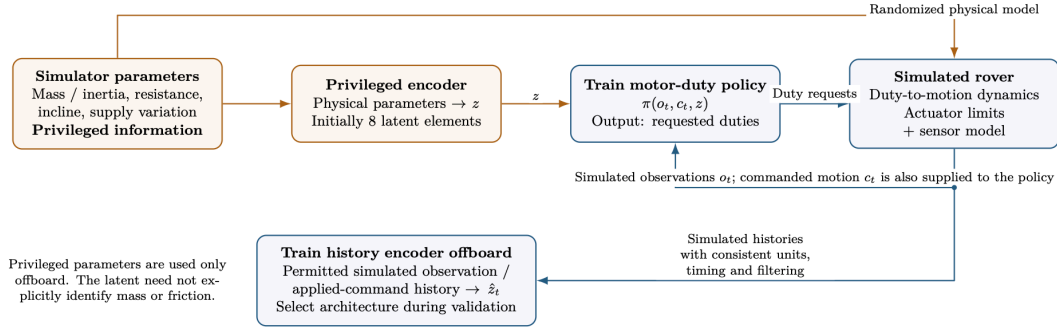
E2 Motion measurements shall resolve HL1 errors over the test window. Initial uncertainty allocations are ≤ 0.005 m/s for surface velocity and ≤ 0.025 rad/s for yaw rate. Verification: Qualify the complete sensor, mounting, timing, and filtering chain against reference motion; measure latency and track invalid readings. These allocations are unverified design targets. A result is inconclusive if uncertainty is too large; encoder speed will not silently replace missing ground-motion data.

2.6 Onboard learning and simulation

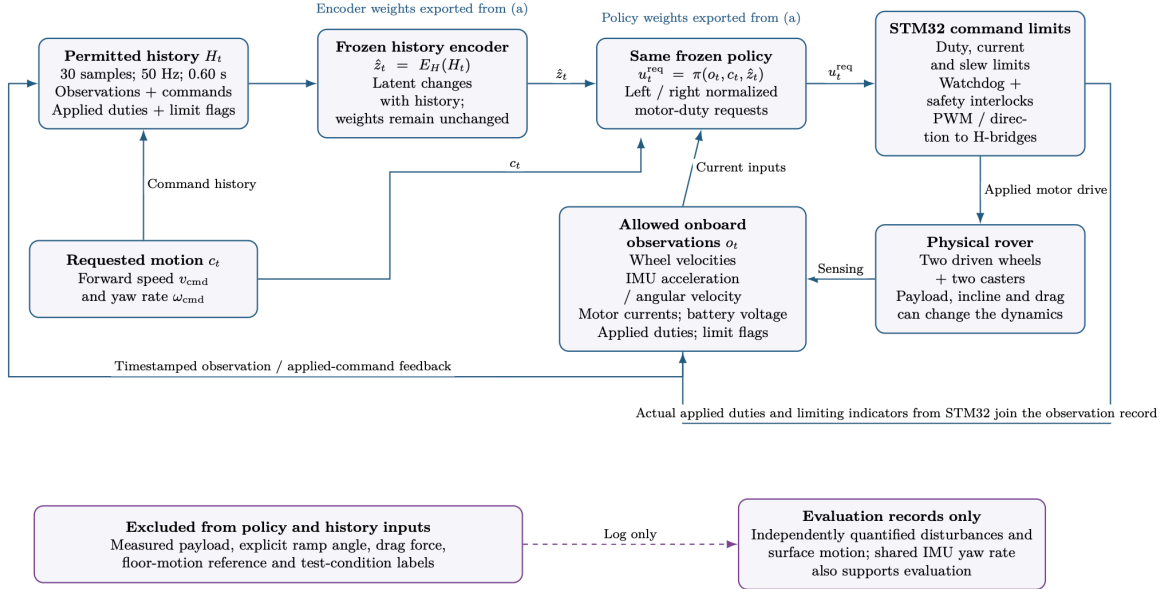
Training will run offboard in Isaac Lab on an available GPU workstation [17]. The model will capture the dominant duty-to-motion dynamics: motor effort, mass/inertia, drivetrain resistance, incline, supply variation, and actuator limits. Measured duty/speed/current behavior, acceleration, coast-down, and delay will establish a nominal model and realistic randomization ranges. Sensor noise and filtering will be included at the fidelity needed for transfer. The project does not require a complete high-fidelity model of every contact or electrical transient.

(a) Offboard training in Isaac Lab

Identify a nominal model from rover characterization; randomize dynamics, sensing and actuator limits.



(b) Onboard deployment: 50 Hz policy loop



Fixed-latent comparison: replace $\hat{z}_t$ with a nominal constant latent; retain the same frozen policy and limits.

No online weight updates or disturbance-specific switching. Full-loop deadline: 20 ms; inference target: below 10 ms.

Figure 4. Privileged training and deployable history inference. Only the upper training path receives simulator dynamics parameters. Deployment uses permitted onboard measurements and applied commands. Frozen weights are retained across final test conditions; adaptation occurs through the history-derived latent.

A privileged encoder will map randomized physical parameters to a compact latent, initially eight elements. The policy will learn motor-duty commands from that latent, current observations, and requested motion. A history encoder will infer the latent from onboard signals, initially 30 samples at 50 Hz. Architecture and history length may be selected during validation and are then frozen. The representation need not identify physical mass or friction explicitly.

Inputs include wheel velocities, acceleration, angular velocity, motor currents, battery voltage, previous applied duties, requested motion, and limiting indicators. Training and deployment use consistent units, timing, and filtering. Gravity sensed by the onboard IMU is a permitted indirect cue. Measured payload, explicit ramp angle, drag force, floor-motion reference, and test labels are excluded. No disturbance-specific controller switching or online weight updates are used.

L1 The deployed model shall infer its dynamics representation from the permitted history using unchanged weights across final conditions. *Verification:* Record model hashes and input schemas before testing; compare adaptive and constant-latent runs using the same policy checkpoint.

L2 Simulation and inference shall preserve the physical actuator and observation constraints. *Verification:* Compare simulated and measured characterization traces; benchmark complete inference on Pi 4 with an initial inference-time target below 10 ms, then verify the full-loop deadline in HL3.

2.7 Baselines and controlled experiments

Three controllers will be evaluated on the same rover: fixed-gain wheel PI with feedforward and anti-windup; the learned policy with a nominal constant latent; and the same learned policy with the history-derived latent. The PI gains and feedforward map will be tuned normally on nominal and allowed validation conditions, then frozen. The nominal latent will be produced from the calibrated nominal model and fixed before tests. All modes will share sensing calibration, duty/current limits, command slew rules, and observation timing.

The primary profile is a short straight acceleration and constant-speed sequence. Payload and incline trials include acceleration so that mass effects are visible. A drag change occurs after nominal tracking begins. A separate level-floor test uses positive and negative yaw-rate commands within validated wheel limits. Curved paths and combined forward/turning disturbance tests are optional extensions. Payloads are changed only while stopped; final controller settings remain unchanged.

We will collect five valid repeats per controller for nominal, 25% payload, 50% payload, incline, and drag conditions, and five repeats of the separate nominal turning profile. Controller order is randomized or counterbalanced. Matched repeats use the same commands, start conditions, and comparable battery-voltage and motor-temperature ranges. Settings, analysis windows, and exclusion rules are fixed before final data collection. More trials may resolve uncertainty, but all valid outcomes from the declared test series will be retained.

A 50% payload plus 5° incline condition will be reserved from physical tuning and tested with the frozen controllers as an additional combined-disturbance evaluation. It may lie within the simulator randomization range; it is not claimed to be unseen during simulation training. Five repeats per controller will be reported separately, without an additional required improvement percentage. Any later retraining creates a new experiment.

2.8 Metrics and acceptance rules

$$\text{RMSE}_v = \sqrt{[(1/N) \sum_k (v_{\text{ref},k} - v_{\text{cmd},k})^2]} \quad (1)$$

Here v_{ref} is calibrated surface velocity along the rover forward axis, v_{cmd} is requested velocity, and N is the synchronized sample count in the predefined window. On the ramp, speed is measured along the surface. Yaw-rate RMSE uses calibrated IMU angular rate. The same fixed filtering and alignment method is applied to every controller. No absolute-position or drift-free-heading claim follows from these measurements.

$$\text{Improvement (\%)} = 100 \times (R_{\text{baseline}} - R_{\text{adaptive}}) / R_{\text{baseline}} \quad (2)$$

Compute RMSE for each trial, then report the mean and spread by controller and condition. HL2 applies to the drag condition specified in advance, not the most favorable condition selected afterward. The fixed-latent mean RMSE must exceed twice the validated velocity uncertainty, and its reduction must exceed the assessed uncertainty of the RMSE difference. Otherwise the comparison is inconclusive. Report all PI and fixed-latent comparisons, including negative results, and paired differences across repeats; five trials support a bounded prototype evaluation, not broad statistical generalization.

Drag onset is the first crossing of the midpoint between measured pre-change and post-change force levels that persists for 50 ms. Correct for measured acquisition/filter delay. Report the actual force rise time. Recovery ends at the first entry into both HL1 error bands that persists for 0.5 s. The 1.5 s recovery target is provisional until characterization; it is not relaxed after final results are seen. No recovery within the trial is a failure. Secondary outputs are peak error, RMS current, saturation fraction, inference latency, and missed deadlines.

V1 Evaluation shall isolate the contribution of history-based adaptation and preserve adverse outcomes. *Verification:* Retain raw synchronized logs, controller identifiers, model hashes, all valid repeats, exclusion

reasons, and analysis code. Plot commanded and measured motion alongside force, duty, current, and limit flags.

2.8.1 Subsystem interfaces and acceptance conditions

The block diagram will use the seven subsystem IDs in Table 3. Each subsystem contributes to a high-level requirement through the stated function. The following values are assembled-system acceptance targets, not copied component ratings. Functional requirements and verification procedures in Sections 2.2–2.8 apply together with these interface limits.

Table 3. Subsystem traceability and quantitative interfaces.

Subsystem and overview location	Contribution	Interface or acceptance condition
S1 Mechanical platform and actuation — 2.2	HL1: support loads and produce motion	25–50% added payload; proposed 5° ramp; qualify joint wheel-speed/current envelope and maintain both drive contacts.
S2 Real-time control and communication — 2.3	HL1, HL3: apply commands and enforce freshness	20 kHz PWM; safety service ≤ 1 ms; 100 Hz telemetry; 230400-baud 3.3 V UART; command timeout ≤ 101 ms.
S3 Proprioceptive sensing — 2.3	HL1, HL2: calibrated onboard observations	Current ± 1.5 A with $\leq \pm 0.05$ A error; wheel-speed steady-state error $\leq \pm 0.005$ m/s over 0.05–0.30 m/s equivalent wheel speed; battery error $\leq \pm 0.10$ V.
S4 Power and safety — 2.4	HL3: valid rails and independent shutdown	5 V rail: 4.85–5.15 V at up to 3.2 A; 3.3 V rail: $\pm 3\%$ at up to 150 mA; initial hardware stop electrical response ≤ 10 ms.
S5 Evaluation sensing — 2.5	Verify HL1, HL2; isolate reference data	Weighed payload, measured angle, one drag-force channel, floor-motion reference, and shared IMU yaw rate. Validate the uncertainty targets in Section 2.5.
S6 Simulation and learned control — 2.6	HL1, HL2, HL3: history-based adaptation	50 Hz; initially 30 samples and eight latent elements; inference target < 10 ms; full loop ≤ 20 ms; frozen weights.
S7 Baselines and evaluation — 2.7–2.8	Verify all high-level requirements	Five valid repeats per controller and defined condition; common commands and limits; all valid adverse outcomes retained.

S3 observations shall update at least at 100 Hz, carry acquisition timestamps and validity flags, and be no more than 30 ms old when used by the policy. Verify wheel velocity against a rotation reference, current against a calibrated current source/reference, and battery voltage against a reference meter. Wheel rotation is not assumed equal to ground motion during slip.

S2 frames will include type/version, length, sequence, timestamp, validity, applied/requested duties and CRC. Proposed maximum lengths are 128 bytes for telemetry and 32 bytes for commands. Invalid, repeated or stale commands shall neither update duty nor refresh the watchdog. Nonfinite model outputs shall cause rejection and safe disable.

S5 force and floor-motion data shall retain acquisition timestamps and validity flags. Characterize force repeatability, transition time, and measurement delay before final trials. Evaluation records must not enter policy/history inputs. Poor sensing or a slow disturbance transition cannot establish rapid recovery.

2.9 Tolerance analysis of signed current sensing

Motor current is a critical observation and a protection input. The channel must measure positive and negative winding current despite PWM common-mode switching without saturating the 3.3 V ADC. The analysis below uses the selected INA240A1 gain of 20 V/V and 33 mΩ, 1% shunt. A shunt temperature coefficient no greater than 50 ppm/°C will be selected. The data sheet specifies a maximum initial gain error of 0.2% and input offset of 25 μV under its stated conditions [4]. Design acceptance must also cover PCB noise and ADC calibration.

$$V_{out} = V_{ref} + G R_s I = 1.65 \text{ V} + (0.660 \text{ V/A}) I \quad (3)$$

We will qualify the calibrated channel over ±1.5 A, providing measurement headroom around the initial 1.2 A driver limit. At nominal values, the output spans 0.660–2.640 V. Assuming a qualified 3.3 V rail within ±3%, reference at half that rail, and a conservative 1.27% combined shunt/gain scaling error including shunt temperature drift, the maximum signal excursion is $1.5 \times 0.660 \times 1.0127 \approx 1.003 \text{ V}$. Combining worst-case reference endpoints and a further ±10 mV output error gives a conservative overall envelope of approximately 0.588–2.712 V.

Even using the lowest 3.201 V rail, this envelope lies within a deliberately restricted output/ADC design window of 0.200–3.001 V. Thus the proposed range has at least 0.289 V of margin to that conservative window. This check is conditional on the reference and filtering implementation meeting the stated assumptions; a rail sweep and bidirectional current injection will verify it.

Table 4. Worst-case current error allocation at $|I| = 1.5 \text{ A}$.

Contribution	Assumption or allocation	Current error
Shunt + amplifier scale	1.05% shunt including temperature + 0.21% amplifier	18.90 mA
ADC / reference residual gain	≤0.50% after calibration	7.50 mA
Amplifier input offset	25 μV + 0.25 μV/°C × 10°C, divided by 33 mΩ	0.84 mA
Residual output error	≤10 mV after zeroing, filtering, and synchronized acquisition	15.16 mA
Worst-case sum	Arithmetic sum, not root-sum-square	42.40 mA

$$|\Delta I| \leq 1.5 \text{ A} \times 0.0176 + (27.5 \text{ μV}) / (0.033 \text{ Ω}) + (0.010 \text{ V}) / (0.660 \text{ V/A}) \quad (4)$$

Equation (4) gives approximately 0.0424 A, below a proposed ±0.05 A calibrated-channel acceptance band near room temperature (25±10°C). The 0.5% ADC/reference and 10 mV residual terms are allocations to verify, not guaranteed values. The aggregate 10 mV covers remaining zero-reference error, PWM pickup, common-mode effects, filter mismatch, ADC settling, quantization, and noise after calibration. Quantization at a 12-bit, 3.3 V ADC is approximately 1.22 mA per count and is included within the residual allocation; resolution does not establish accuracy.

$$P_{shunt,max} = I^2 R_s = (1.5 \text{ A})^2 \times 0.033 \text{ Ω} = 0.0743 \text{ W} \quad (5)$$

A ≥1 W shunt therefore has substantial steady-state dissipation margin at this measurement endpoint. Kelvin routing, reference decoupling, ADC sampling-settling time, and PWM-edge blanking remain necessary. The bench test will sweep both current polarities and operating PWM duties against a calibrated reference, including near-zero current and motor reversal. If the residual allocation fails, the channel must be corrected before its data are used to train or evaluate adaptation.

2.10 Drive feasibility and mechanical margins

The sensing analysis establishes a critical circuit function. A separate first-order drive calculation checks whether the proposed physical disturbances are plausible before fabrication. For sizing only, assume an unloaded mass no greater than 2.0 kg, total mass 3.0 kg with 50% payload, wheel radius 0.040 m, rolling-resistance coefficient 0.03, acceleration 0.10 m/s², a 5° incline, and 1.0 N drag. These are design assumptions to measure, not known properties of the rover. This calculation combines all three loads as a conservative sizing case; Table 1 does not require a three-disturbance final trial.

$$F_{req} = ma + mg \sin \theta + C_{rr} mg \cos \theta + F_{drag} \quad (6)$$

$$F_{req} \approx 0.300 + 2.565 + 0.880 + 1.000 = 4.745 \text{ N} \quad (7)$$

$$\tau_{wheel} = F_{req} r/2 \approx 0.0949 \text{ N}\cdot\text{m per motor} \quad (8)$$

A 20% sizing allowance raises the per-motor torque estimate to 0.114 N·m. The selected motor's listed extrapolated stall torque is approximately 8.5 kg·cm, or 0.834 N·m; stall torque is not a continuous operating rating [7]. A rough linear torque/current interpolation between 0.10 A no-load and 1.8 A stall predicts about 0.33 A at the sizing torque. This estimate neglects temperature, detailed gearbox losses, voltage sag, and motor variation. It supports bench characterization, not a claim that the final rover will necessarily meet every target.

Pololu advises generally keeping continuous brushed-motor current near or below 25% of stall current [18]. For this motor that gives an initial conservative reference of 0.45 A. The final sustained limit must be established by thermal tests of the installed drivetrain; 1.2 A is a short-duration hardware limit, not an allowed continuous load. Current protection may constrain acceleration or reduce the validated envelope.

$$v_L = v - b\omega/2, \quad v_R = v + b\omega/2 \quad (9)$$

With proposed track width $b = 0.20$ m, $v = 0.20$ m/s and $\omega = 1$ rad/s request wheel speeds of 0.10 and 0.30 m/s. The outer wheel would require about 71.6 rpm. Although nominal no-load speed is approximately 100 rpm, load and manufacturing variation reduce available speed; the upper forward and yaw commands therefore cannot be accepted independently. Commands will be jointly limited to the loaded wheel-speed envelope identified on the real rover.

Traction also depends on weight carried by the driven wheels. If the measured drive-wheel load share is 60% and the tire/floor friction coefficient is 0.5, the illustrative available traction is $0.5 \times 0.6 \times 3.0 \times 9.81 \times \cos(5^\circ) \approx 8.80$ N, above the 5.69 N force with sizing allowance. Neither coefficient is assumed guaranteed. A pull test and individual wheel-load measurements will establish the margin; caster compliance or height adjustment will preserve drive contact.

Mechanical acceptance will also check that the projected center of mass remains inside the actual support polygon with clearance during ramp traversal, acceleration, and turning. Battery and payload will be kept low and centered. Ramp transitions, caster swivel behavior, fixture clearances, and tether height must be tested directly because a static force calculation does not prove rollover or snag resistance.

3 Ethics safety societal impact and standards

3.1 Ethical and societal considerations

The intended benefit is more predictable transport by small mobile robots when carried loads or travel conditions change. Better adaptation could reduce manual retuning and motion errors, but it may also create misplaced trust in a controller whose behavior is reliable only within its tested domain. We will describe the rover as an experimental indoor platform and publish its limits, failed recoveries, and uncertainty alongside favorable results. We will not infer general autonomous-navigation or human-safety capability from trajectory-tracking tests.

The IEEE Code of Ethics calls for public welfare and honest technical claims [19]. We will tune PI fairly, use common actuator limits, retain adverse outcomes, and report unresolved comparisons. The onboard floor sensor measures local surface motion; no overhead video system is required. Any optional demonstration recording will avoid identifying bystanders where possible. Reused parts and repairable wiring can reduce waste, but no measured net environmental benefit is claimed.

3.2 Project specific hazards and controls

Motion hazards include wheel pinch points, unexpected acceleration, dropped payloads, snagged drag lines, and rollback on an incline. We will use guarded moving parts where accessible, secure cargo and battery mounts, a clear test perimeter, a visible armed-state indicator, and an accessible latching emergency stop. Initial firmware and driver tests will use raised or restrained wheels. Ramp testing will include side guides and an independent catch restraint, with no person downhill of the rover. A driver-disabled rover can still coast or roll, so personnel protection cannot depend solely on software or nSLEEP.

Electrical hazards include short circuits, hot motors or drivers, incorrect charging, and regenerative overvoltage. The power path will include a correctly rated fuse close to the pack, insulated terminals, strain relief, polarity protection, and current/temperature qualification. The matched LiFePO4 charger will be used with the rover powered off in an appropriate supervised charging area. Damaged packs or wiring will be removed from service. Thermal and stall tests will be bounded by conservative limits rather than intentionally operating a motor at extrapolated stall ratings.

Learning-specific hazards include out-of-distribution actions, corrupted observations, stale communication, and unsafe startup history. The STM32 will enforce limits independently of model output, reject malformed/stale commands, and remain disarmed until valid sensing and an explicit enable condition are established. A malformed neural-network output will cause a safe disable rather than being cast directly to a PWM command.

3.3 Applicable standards and engineering guidance

ISO 12100:2010 supplies a relevant framework for identifying hazards, estimating risk, and selecting protective measures across setup, operation, and maintenance [20]. We will apply that framework to the rover, ramp, drag fixture, power system, and test procedure. ISO 13850:2015 provides emergency-stop design principles relevant to a maintained stop state and deliberate reset [21]. These standards guide the design; this student prototype is not claimed to be certified to them or to implement a safety-rated control architecture.

Manufacturer electrical limits, battery charging instructions, PCB assembly requirements, and the laboratory's operating rules will govern implementation. SPI, UART, and GPIO interfaces will follow the voltage and timing limits of the connected devices. Before testing, the team will document the hazard review, stop behavior, allowable operating envelope, and responsible operator. Any change affecting load, current limits, or the fixture will trigger a review before experiments resume.

3.4 Misuse and wider impact

Accidental misuse could include placing cargo outside the permitted region, loading the wrong test configuration, routing the tether near a wheel, or starting with stale observation history. Marked loading locations, versioned configurations, fixture inspection, connector labels, and explicit history-validity checks will address these risks. Intentional bypass of the stop circuit, inflated current limits, or supply of disturbance labels would invalidate the experiment and could create unsafe motion. Safety-related changes will therefore be logged and reviewed before further testing; the platform is not claimed to be tamper-proof.

Potential economic benefit comes from reduced retuning and more consistent operation, but additional sensing, computation and training also impose costs. No measured savings or net environmental benefit are claimed. Global differences in surfaces, maintenance, loading and component availability limit transfer of the results. Users also differ in technical familiarity and interpretation of colors; plain labels and a physical stop control will supplement status indicators. Tests will not obstruct accessible routes.

3.5 Campus policy and regulatory considerations

University CAM RP-17 establishes environmental health and safety responsibilities for students and other participants in university operations [22]. The team will follow course/laboratory procedures and document hazards, arming and shutdown before powered tests. DRS electrical-safety guidance supports appropriate insulation, wiring inspection and electrical-hazard documentation [23]. Low battery voltage does not eliminate short-circuit and heating hazards.

Battery charging and disposal will follow manufacturer instructions and campus DRS guidance [24]. The team will use the matched charger, protect terminals, remove damaged packs from service and route unwanted batteries through the campus waste process. No improvised treatment or ordinary-trash disposal is planned. Federal universal-waste rules in 40 CFR Part 273 and Illinois rules identified under Part 733 are relevant to applicable end-of-life battery handling [25] [26]. Institutional waste determinations and disposal will use DRS procedures rather than assuming household exemptions.

This scope is a supervised indoor educational prototype. Public-road operation, commercial sale and operation around untrained users are not established by this proposal and would require a separate applicability and safety review. Use of ISO design guidance does not establish formal certification or guarantee that every possible regulatory obligation has been resolved.

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