ECE 445

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Project Proposal

Two-Wheel Differential Drive Ant-Weight Battlebot

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1 Introduction

1.1 Problem

Ant-weight combat robots (under 2 lbs) must operate within strict constraints: 3D-printed thermoplastic construction, wireless control, and maximum 4S LiPo battery. These robots face severe weight-to-performance trade-offs where every gram allocated to weapons reduces structural integrity or battery capacity. The primary engineering challenges include maintaining mobility and weapon effectiveness under high-impact conditions, preventing immobilization when attacked from unexpected angles, and ensuring electrical stability during weapon spin-up and collision events. Under competition rules, losing mobility for more than 10 seconds results in knockout, making robust mechanical design and reliable power management critical for competitive success.

1.2 Solution

We propose a two-wheel differential drive ant-weight robot featuring a horizontal drum spinner weapon and dual front wedge system. The robot uses two independently-driven wheels for propulsion and differential steering, enabling zero-radius turns and superior maneuverability. While a two-wheel design sacrifices drive redundancy compared to four-wheel configurations, it reduces weight and mechanical complexity, freeing mass budget for structural reinforcement. The offensive system integrates a motorized horizontal drum mounted at the front with ground-level wedges positioned beneath it. The wedges serve dual purposes: they act as tertiary support points (forming stable three-point contact with the drive wheels) and function as scooping mechanisms to lift opponents into the drum's impact zone.

Stability is ensured through passive geometric design. The chassis features low center of gravity with the battery mounted horizontally between the drive wheels at the lowest position. Wide wheelbase maximizes rollover resistance. Drive wheels are enclosed in protective armor shells with outward-angled profiles to deflect attacks and minimize exposed contact area.

The electrical system is built around an ESP32 microcontroller with integrated WiFi and Bluetooth for wireless control. A custom PCB houses the ESP32, voltage regulation, dual H-bridge motor drivers for drive wheels, and ESC interface for the weapon motor. An MPU-6050 IMU provides orientation and acceleration data, enabling an experimental investigation into gyroscopic stabilization: by modulating weapon speed in response to detected flip motion, the system explores whether meaningful counter-torque can be generated at the ant-weight scale. Theoretical analysis predicts modest correction (5-15°), and empirical testing will characterize the actual feasibility boundary. Regardless of gyroscopic effectiveness, invertible chassis geometry ensures operational mobility even if completely inverted, with wheel diameter selected to exceed chassis height. The power distribution implements decoupled rails: high-current path for motors and regulated 3.3V rail for logic circuits, preventing voltage sag from weapon transients. Safety is ensured through communication link monitoring with automatic motor shutdown within 2 seconds of signal loss.

1.3 Visual Aid

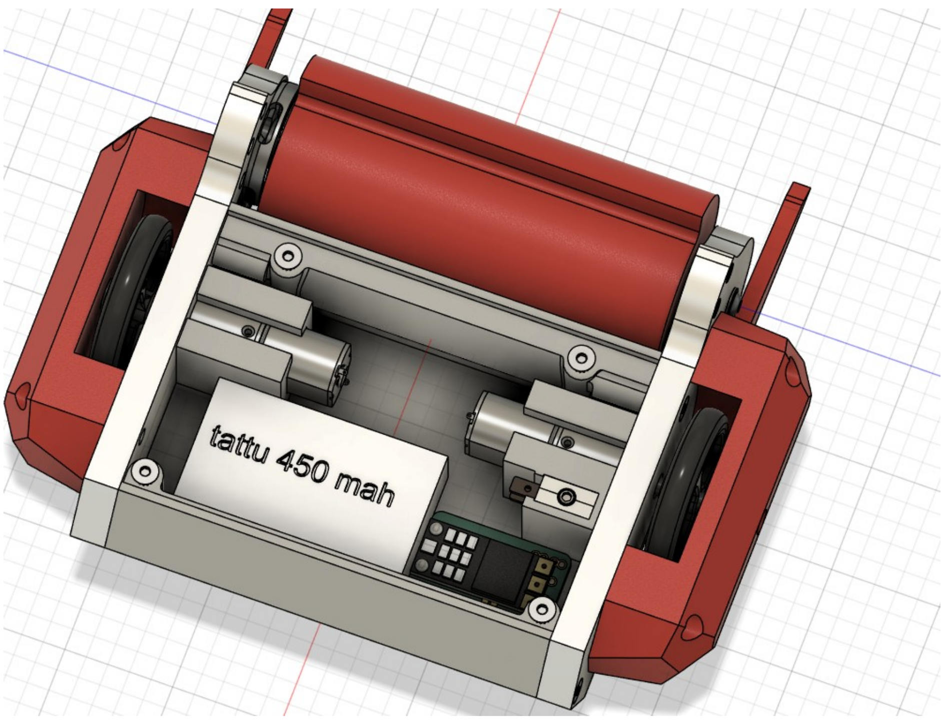

Figure 1: Concept CAD showing the two-wheel differential drive layout with horizontal drum weapon from UIUC DPD.

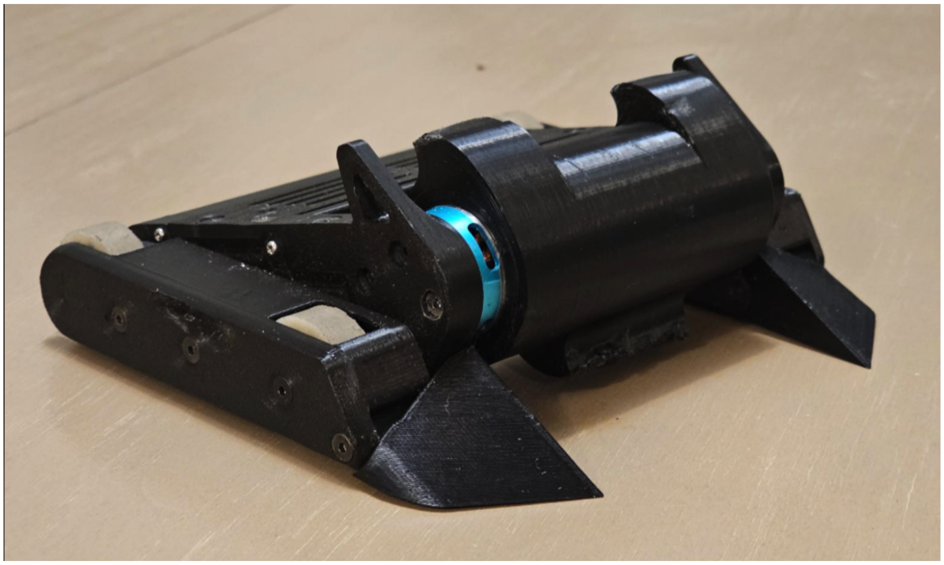

Figure 2: Battlebot implementation photo (Source: https://www.reddit.com/r/battlebots/comments/1misa9t/after_starting_out_almost_a_year_ago_with_my/)

1.4 High-Level Requirements

1. **Mobility:** Minimum acceleration of 1.5 m/s^2 and 180° rotation in under 1 second.
2. **Weapon Performance:** Horizontal drum reaches 150+ mph tip speed within 5 seconds and maintains it for 3-minute operation.
3. **Stability & Safety:** Rollover resistance $\geq 50°$; minimum 0.5 m/s inverted mobility. Symmetric chassis (armor variance $\leq$ 2 mm) with wheels extending beyond chassis height. Wireless latency $\leq$ 100 ms; emergency shutdown within 2 seconds of signal loss or manual command.

1.5 Experimental Features

Gyroscopic Stabilization: As a research objective, the system will modulate weapon motor speed in response to IMU-detected flip events to generate gyroscopic counter-torque. Target correction range of 5-15° flip angle reduction will be empirically validated through controlled drop testing to characterize the practical limits of this technique at the ant-weight scale.

2 Design

2.1 Block Diagram

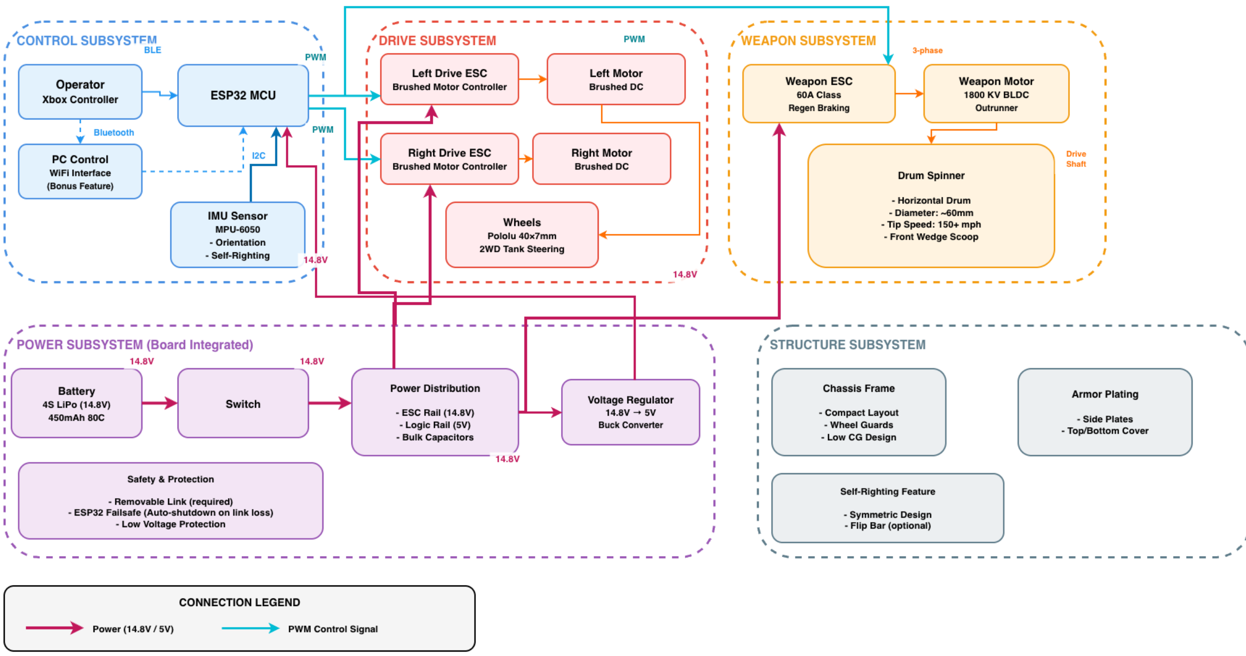

Figure 3: System Block Diagram

2.2 Subsystem Overview

The robot consists of six subsystems as shown in the block diagram.

Control Subsystem: Receives operator commands through one of two wireless configurations: (1) Xbox controller connects via Bluetooth to a PC, which relays commands to the ESP32 over WiFi, or (2) Xbox controller connects directly to the ESP32 via Bluetooth. The ESP32 microcontroller generates PWM control signals for two drive ESCs and one weapon ESC, provides IMU-based telemetry, and implements failsafe logic to detect communication loss and trigger emergency shutdown. Additionally, the control subsystem runs an experimental gyroscopic correction algorithm that modulates weapon speed in response to IMU-detected flip events.

Drive Subsystem: Two brushed DC motors with dedicated ESCs provide differential steering. Left/right motors receive independent PWM commands enabling tank-style maneuvering with zero-radius turns. Wheels are directly coupled to motor shafts. Powered by

14.8V from power subsystem.

Weapon Subsystem: Horizontal drum spinner driven by brushless motor (2200 KV). Weapon ESC (60A-class, with regenerative braking support) receives PWM from control and drives motor with 3-phase current. The higher current rating accommodates transient peak loads during weapon spin-up and post-impact recovery. Drum rotates at high speed (150+ mph tip) to deliver kinetic impacts. Regenerative braking brings the weapon to a full stop within 60 seconds of power removal, satisfying competition safety requirements. Front wedges scoop opponents into drum engagement zone.

Power Subsystem: 4S LiPo battery (14.8V nominal, 450mAh, ≥80C continuous discharge, e.g., Gaoneng 4S 450mAh 80C/160C or equivalent) with fingertech mini power switch (removable link). Power distribution provides ESC rail (14.8V direct from battery) and regulated logic rail (5V via buck converter) with bulk capacitors ($\geq 1000\ \mu$F) to prevent voltage sag during weapon transients. Voltage regulator steps 14.8V to 5V. Status LEDs indicate main power (always on) and active wireless connection. Safety: ESP32 failsafe and low-voltage protection.

Structure Subsystem: 3D-printed chassis (PETG/PC/TPU) with compact layout and low center of gravity. Wheel guards protect drive motors. Armor plating provides impact protection. Front wedges serve as tertiary support and scooping mechanism.

Stability & Recovery Subsystem: Flip defense relies primarily on passive geometry and invertible design. Wide wheelbase and low center of gravity provide exceeding 50° static rollover resistance. Symmetric top/bottom chassis geometry ensures operational mobility when inverted, with drive wheels extending beyond the chassis in either orientation. As a secondary research component, MPU-6050 IMU monitors orientation at 100 Hz; when flip is detected, ESP32 modulates weapon motor speed to generate gyroscopic counter-torque. Theoretical analysis predicts 5-15° correction at the ant-weight scale—this subsystem serves to experimentally validate and characterize the practical limits of gyroscopic stabilization at this weight class.

2.3 Subsystem Requirements

Control Subsystem:

1. Wireless range ≥ 30 feet with latency ≤ 100 ms.

2. Detect communication loss within 500 ms and initiate emergency shutdown.

3. Generate PWM for two drive ESCs and one weapon ESC.

4. Read IMU data via I2C at 100 Hz for flip detection and gyroscopic stabilization control.

Drive Subsystem:

1. Linear acceleration ≥ 1.5 m/s^2 from rest.
2. In-place rotation: 180° in under 1 second.
3. Brushed motor ESCs support bidirectional control with adequate current rating.

Weapon Subsystem:

1. Tip speed ≥ 150 mph within 5 seconds of full throttle.
2. Continuous 3-minute operation without thermal shutdown.
3. Mechanically balanced drum to limit vibration.
4. Weapon ESC responds to throttle modulation within 100 ms to enable gyroscopic correction during flip events.
5. Weapon motor braking brings drum to full stop within 60 seconds of power removal.

Power Subsystem:

1. Battery provides 3-minute continuous operation under typical combat loading.
2. Battery continuous discharge rating $\geq$ 80C (36A continuous) to accommodate weapon transients.
3. Regulated 5V logic rail remains within $\pm 5\%$ during weapon transients.
4. Manual power switch with removable link for safety compliance.
5. Status LEDs visible from outside: one for main power, one for active wireless link.

Structure Subsystem:

1. Total weight < 2.0 lbs including battery.
2. Low center of gravity with battery at lowest position.
3. Front wedges provide stable three-point support.

4. Armor withstands repeated impacts without catastrophic failure.
5. Symmetric top/bottom geometry: armor thickness variance ≤ 2 mm for invertible operation.
6. Wheel clearance: drive wheels extend beyond maximum chassis height to ensure ground contact in both orientations.
7. Rollover resistance angle $\geq 50°$ under static loading conditions.

Stability & Recovery Subsystem:

1. IMU sampling rate ≥ 100 Hz with processing latency ≤ 20 ms.
2. Flip detection threshold: pitch/roll rate > 5 rad/s triggers gyroscopic correction.
3. Gyroscopic correction target: 5-15° flip angle reduction (to be empirically validated; actual effectiveness at ant-weight scale is a research question).
4. Inverted mobility: robot achieves minimum 0.5 m/s speed in inverted configuration.
5. Passive flip bar (if included) achieves self-righting within 3 seconds on flat surface.

2.4 Tolerance Analysis

2.4.1 Drive Motor Torque Calculation

Required Acceleration: $a = 1.5$ m/s^2

Drive Force: For total mass $m = 0.9$ kg (2 lbs):

$$F_{drive} = m \cdot a = 0.9 \times 1.5 = 1.35 \text{ N}$$

Torque per Motor: For estimated wheel radius $r \approx 0.015$–0.020 m and two-wheel drive:

$$\tau_{motor} = \frac{F_{drive} \cdot r}{2} = \frac{1.35 \times 0.020}{2} = 0.0135 \text{ N·m} = 13.5 \text{ mN·m}$$

Candidate Motor: Brushed DC gearmotor (final selection based on weight and packaging constraints). Required specifications:

- Output torque: ≥ 13.5 mN·m (target: $\sim$50 mN·m for adequate safety margin)

- Sufficient no-load speed at 14.8V to achieve target ground speed
- Continuous current rating: ≥ 1.5 A per motor

At target speed of 3 m/s with estimated wheel diameter of 30–40 mm, required wheel RPM is approximately 1,400–1,900 RPM, well within typical motor capability.

Verification: Empirical testing with complete assembly to confirm acceleration ≥ 1.5 m/s^2.

2.4.2 Weapon Tip Speed Calculation

Target Tip Speed: $v_{tip} = 150$ mph $= 67$ m/s

Required RPM: For estimated drum diameter $d \approx 60$ mm:

$$\text{RPM} = \frac{v_{tip} \times 60}{2\pi r} = \frac{67 \times 60}{2\pi \times 0.03} = 21,325 \text{ RPM}$$

Motor KV:

$$KV = \frac{21,325}{14.8} = 1,441 \text{ KV}$$

Candidate Motor: 1800 KV BLDC outrunner at 14.8V delivers 26,640 RPM (25% margin over requirement).

Voltage Sag Consideration: Under peak current draw (∼30–35A during weapon recovery after impact), battery internal resistance may reduce terminal voltage to ∼13–14V momentarily. At 13V: 1800 × 13 = 23,400 RPM → tip speed = 73.5 m/s (164 mph), comfortably above 150 mph. Even at worst-case 12V: tip speed = 151 mph, still meeting specification. The higher voltage headroom of 4S provides robust margin against voltage sag.

Verification: Measure RPM with optical tachometer at full throttle to confirm tip speed ≥ 150 mph.

2.4.3 Gyroscopic Stabilization Analysis

Research Motivation: Gyroscopic stabilization through weapon speed modulation is well-established in heavier weight classes (3 lb+), where larger drum inertia produces significant counter-torque. Whether this technique yields meaningful benefit at the ant-weight scale (2 lbs) is an open question that this project aims to investigate experimentally.

Gyroscopic Torque Generation: When IMU detects flip motion (pitch/roll rate > 5 rad/s), ESP32 modulates weapon speed by 30% over 200 ms.

For drum with moment of inertia $I_d \approx 1.35 \times 10^{-5}$ kg·m² at angular velocity $\omega_d = 2233$ rad/s (21,325 RPM):

$$\tau_{gyro} = I_d \frac{\Delta\omega}{\Delta t} = 1.35 \times 10^{-5} \times \frac{670}{0.2} = 0.045 \text{ N·m}$$

Effectiveness Analysis: Typical flip attacks generate torques of 0.5-2.0 N·m on ant-weight robots. Gyroscopic counter-torque ratio:

$$\text{Correction ratio} = \frac{\tau_{gyro}}{\tau_{flip}} = \frac{0.045}{1.0} \approx 4.5\%$$

For a flip that would otherwise reach 180°, correction reduces final angle by:

$$\Delta\theta = 180 \times 0.045 = 8$$

Expected Range: Accounting for detection latency, efficiency losses, and varying attack intensities, theoretical correction range is 5-15°. At the ant-weight scale, this correction is inherently limited by the small drum inertia. However, even modest improvement in landing orientation may increase the probability of landing on chassis edge rather than fully inverted, complementing the invertible geometry.

Comparison Across Weight Classes: Heavier classes (3+ lbs) with drums 5-10× more massive achieve 20-40° correction. This project will establish whether the effect remains practically useful at the 2 lb boundary, contributing data to an area with limited published characterization.

Verification: Controlled drop/impact testing with IMU data logging across multiple scenarios. Data will be compared against identical tests with gyroscopic correction disabled to isolate the effect.

2.4.4 Rollover Resistance Calculation

Geometric Stability: For estimated wheelbase $w \approx 100$–130 mm and center of gravity height $h_{CG} \approx 25$–30 mm (final dimensions determined during CAD phase):

Rollover angle under ideal conditions (maximum tilt before tipping), using representative values $w = 120$ mm, $h_{CG} = 26$ mm:

$$\theta_{rollover} = \arctan\left(\frac{w/2}{h_{CG}}\right) = \arctan\left(\frac{60}{26}\right) = 66.6$$

Even at the narrow end of the design range ($w = 100$ mm, $h_{CG} = 30$ mm): $\theta = \arctan(50/30) =$ 59, still exceeding the 50° requirement. This provides robust resistance to wedge attacks and side impacts across the anticipated dimension range.

Verification: Tilt test on adjustable platform to confirm stability up to calculated angle.

2.4.5 Invertible Geometry Verification

Wheel Clearance Requirement: For invertible operation, wheels must contact ground before chassis in both orientations.

Design Constraint: Wheel diameter d_w must exceed maximum chassis height h_c so that wheels contact the ground before the chassis in both orientations:

$$\Delta h = \frac{d_w - h_c}{2} > 0$$

For example, with estimated wheel diameter $d_w \approx 40$ mm and chassis height $h_c \approx 35$ mm, clearance $\Delta h = 2.5$ mm. Final wheel and chassis dimensions will be selected during the CAD phase to ensure adequate clearance margin, accounting for 3D printing tolerances.

Verification: Physical measurement of assembled robot in both orientations to confirm wheel-ground contact.

2.4.6 Power Budget

Drive Motors: Two brushed DC motors at estimated 1.5A continuous each:

$$P_{drive} = 2 \times 14.8\text{V} \times 1.5\text{A} = 44.4 \text{ W}$$

Weapon Motor: BLDC at estimated 8A average (accounting for idle spinning at 2–4A and periodic acceleration after impacts at 15–25A):

$$P_{weapon} = 14.8\text{V} \times 8\text{A} = 118.4 \text{ W}$$

Electronics: ESP32, IMU, LEDs at ~500mA from 5V rail, through buck converter at 90% efficiency:

$$P_{logic} = \frac{5\text{V} \times 0.5\text{A}}{0.9} = 2.8 \text{ W}$$

Total Average Power: $P_{total} = 44.4 + 118.4 + 2.8 = 165.6$ W

Battery Energy: $E = 14.8\text{V} \times 0.45\text{Ah} = 6.66$ Wh

Runtime:

$$T = \frac{6.66 \text{ Wh}}{165.6 \text{ W}} \times 60 = 2.41 \text{ minutes}$$

This calculation represents sustained combat conditions with active weapon engagement. The 2.4-minute runtime is tight but viable for the 3-minute match requirement, as actual matches include periods of maneuvering without weapon contact. Conservative driving or strategic weapon usage extends runtime beyond the calculated minimum.

Peak Current Analysis: Drive (3A each) + Weapon (30A transient during post-impact recovery) + Logic (0.5A) = 36.5A peak. With an 80C battery (36A continuous capacity), brief transient peaks are tolerated. The higher voltage of 4S reduces current draw by 33% compared to 3S at equivalent power, significantly easing thermal and electrical stress on all components.

3 Ethics and Safety

3.1 Ethical Considerations

Safety (IEEE Code 1.1): Combat robots pose risks if safety systems fail. Our design implements multiple protections: communication link monitoring with automatic shutdown (2 seconds), manual emergency stop, and fail-safe defaults (zero throttle on invalid input). We acknowledge wireless communication introduces potential RF interference; future iterations could add redundant safety mechanisms.

Honest Representation (IEEE Code 3.1): Several design aspects require component selection and empirical validation. We commit to rigorous testing before claiming the robot meets stated requirements. Tolerance analysis provides theoretical feasibility; actual performance requires physical validation.

Environmental Impact: LiPo batteries require proper disposal through campus EH&S recycling protocols. 3D-printed components will use recyclable materials where feasible and designs will minimize material waste.

Educational Impact: Combat robotics provides hands-on experience in mechanical design, embedded systems, and power electronics. We may open-source our designs to contribute to the educational community.

3.2 Safety and Compliance

Competition Rules (theirc.org):

- Weight: 2lbs
- Materials: 3D-printed thermoplastics (PETG, PLA+)
- Battery: 4S LiPo maximum
- Control: WiFi or Bluetooth via ESP32
- Emergency shutdown: manual and automatic on link loss
- Status LEDs for power and wireless connection visible from outside
- Weapon must stop within 60 seconds of power removal (braking system)

Wireless Compliance: ESP32-WROOM-32D is FCC-certified under Part 15 for 2.4 GHz WiFi and Bluetooth operation.

Operational Safety:

- Testing in controlled environments (ECE lab/arena); We will not test our robots outside safe environments;
- PPE required: safety glasses, closed-toe shoes;
- LiPo charging with approved chargers and fire-resistant bags;
- We will have a kill switch to ensure operator can disable the battlebot when needed, especially during emergencies;

References

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