TECHNICAL REPORT: ECO-GEAR CONTROLLER (PS3)

Project: The Sentry Rover - Synapse Drive 25

To: Stark Industries Engineering Oversight

From: Aditya Raj Gupta

Subject: Strategy and Implementation of the Failsafe Gear-Shifting Logic

1. Team Information

- **Name:** Aditya Raj Gupta
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- **Branch/Year:** Production and Industrial Engineering (1st Year)

2. Executive Summary

In the aftermath of the high-altitude EMP strike, the autonomous defense capabilities of Stark Industries have been reduced to a single bicycle-dynamics failsafe module. This report outlines the design and implementation of the **Eco-Gear Controller**, a deterministic algorithm designed to navigate the Sentry Rover across a 1D track of varying terrain.

The controller is engineered to balance two competing objectives:

1. **Temporal Success:** Ensuring the rover reaches the finish line before the system's strict time limit expires.
2. **Energetic Efficiency:** Minimizing total Joules consumed by leveraging environmental potential energy and preventing mechanical loss due to wheel slip.

Our solution achieved significant energy savings on the practice track by implementing a state-machine that prioritizes momentum conservation over constant propulsion.

3. Physics of the Dynamic Model

To design an efficient controller, we must first understand the forces acting upon the bicycle rover. The total force (F_{total}) determining the rover's acceleration (a) can be summarized by:

$$F_{total} = F_{drive} + F_{gravity} + F_{drag} + F_{rolling\_resistance}$$

3.1 Gravitational Influence ($F_{gravity}$)

On a 1D track with a slope angle θ:

$$F_{gravity} = -m \cdot g \cdot \sin(\theta)$$

Uphill slopes ($slope > 0$) create a backward force, while downhill slopes ($slope < 0$) provide "free" forward thrust. Our controller is designed to harvest this thrust by setting the gear ratio to 0.0, effectively decoupling the motor and allowing gravity to act as the primary engine.

3.2 Aerodynamic Drag (F_{drag})

At higher velocities, the rover faces air resistance:

$$F_{drag} = -\frac{1}{2} \cdot \rho \cdot v^2 \cdot C_d \cdot A$$

Since drag increases with the square of velocity, there is a "point of diminishing returns" for speed. Our controller targets a steady-state velocity of 6.0 m/s to minimize drag losses while still beating the time limit.

3.3 Friction and Traction (μ)

The maximum drive force the rover can apply before the wheels begin to slip is governed by:

$$F_{max\_traction} = \mu \cdot F_{normal}$$

Where $F_{normal} \approx m \cdot g \cdot \cos(\theta)$. If our F_{drive} exceeds this limit, we enter a "slip event," which consumes high energy without increasing velocity.

4. Controller Strategy: The "Synapse Drive" Logic

The controller utilizes a **Hybrid Heuristic State Machine**. It does not simply react to the current meter; it anticipates the next segment using the track_info metadata.

4.1 State 1: Potential Energy Harvesting (Downhill)

When the telemetry detects a slope < -0.02, the controller enters **Coasting Mode**.

- **Logic:** return 0.0
- **Benefit:** Motor current is cut to zero. Kinetic energy is maintained or increased solely through gravitational potential, yielding the highest possible efficiency score.

4.2 State 2: Predictive Momentum Building (Look-Ahead)

The simulator provides a next_segment tuple. Our controller calculates the distance to this transition.

- **Logic:** If a steep hill ($slope > 0.15$) is within 12m, the controller shifts to a high-torque ratio (3.5) regardless of current flat terrain.
- **Benefit:** By accelerating *before* the hill, the rover hits the incline with high kinetic energy, requiring less total energy to reach the crest.

4.3 State 3: Traction-Aware Torque Capping

To solve the problem of "hidden" low-friction segments, we implemented a dynamic cap.

- **Mathematical Model:** We found through testing that $Gear_{max} \approx \mu \times 5.0$ provides a safe upper bound.
- **Implementation:** gear_output = min(gear_output, mu * 5.0).
- **Benefit:** This prevents energy waste due to wheel spin on mud or ice.

5. Experimental Observations & Results

5.1 Energy Consumption Analysis

Controller Version	Total Energy (J)	Completion Time (s)	Slip Events
Baseline (Standard)	84,200	142.5	14
Eco-Gear v1.0	52,100	158.2	0
Eco-Gear Final	48,900	151.0	0

5.2 Handling of Hidden Tracks

Our controller was tested against randomized μ values. The traction-aware scaling was the most critical feature, allowing navigation of "Ice" segments ($\mu = 0.2$) where baseline controllers typically stall.

6. Known Limitations & Edge Cases

- **Extreme Gradients:** On slopes exceeding 45%, the 6.0 m/s target may be unreachable.
- **Short Segments:** If segments are shorter than 5m, rapid state changes may occur.

7. Conclusion

The **Eco-Gear Controller** is a deterministic, high-efficiency solution for the Sentry Rover platform. By respecting the physical limits of traction and utilizing gravity as a source of energy, we have developed a robust brain for Stark Industries' defense systems.

Status: Ready for final evaluation.