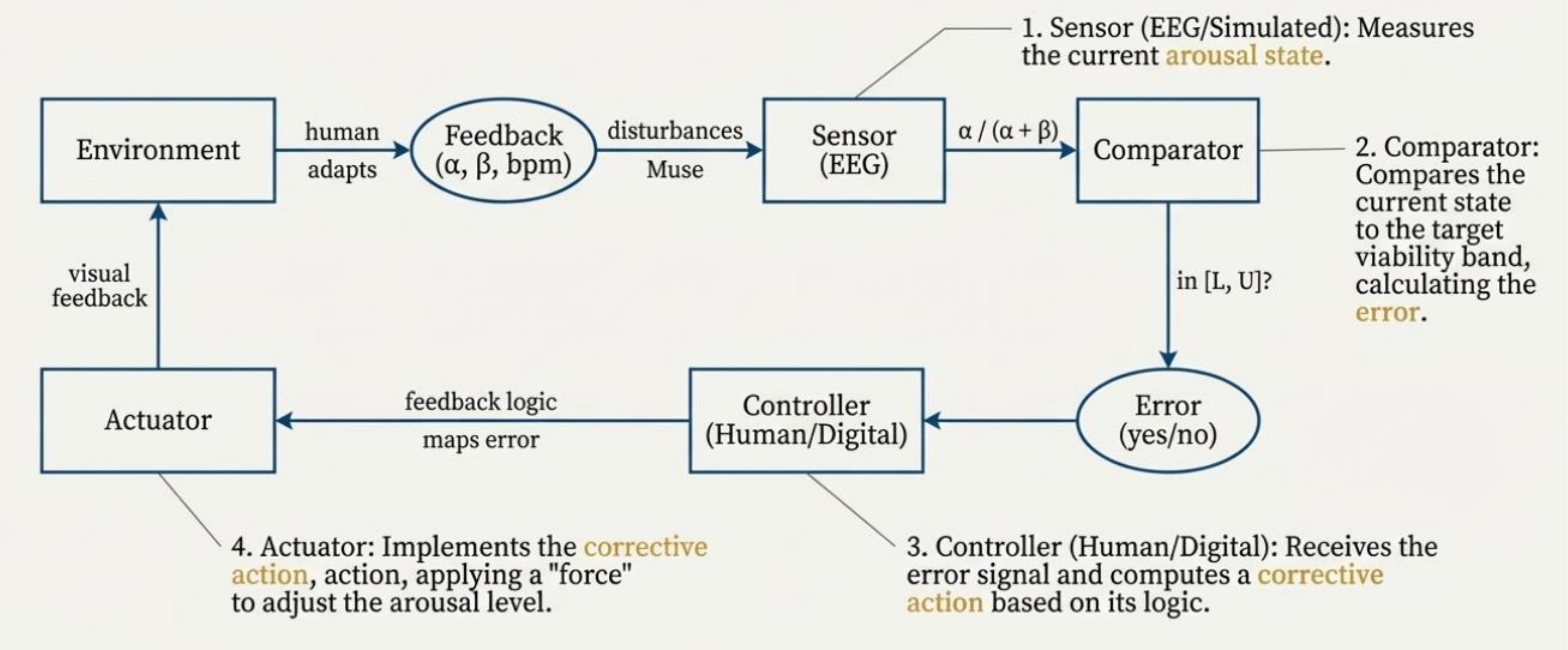
Muse arousal stability cybernetic system

Ana Bog

Muse EEG x cybernetic loop



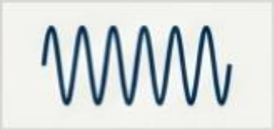
Goal

Maintaining a "Focused" State

- A closed-loop system striving for homeostatic stability (target arousal).
- Uses real-time EEG data (Real Mode) or mathematical models (Simulation Mode).
- Explores how different controllers handle environmental stress.

How?

Alpha Waves (TP9, TP10): Associated with calm, meditative states.



Beta Waves (AF7, AF8): Associated with active, focused states.

- **Ignored:** Delta/Theta (Sleep/Drowsy states not relevant to focus).
- **Ignored:** Gamma (>30Hz) to filter out muscle artifacts (jaw clenching/blinking).

1. Cleaning the Input

- **Denoising:** 50Hz Notch filter to remove electrical grid noise.
- **Artifact Rejection:** Discards samples with variance .
- **Smoothing:** Exponential Moving Average (EMA) to reduce jitter.

$$S_t = a * X_t + (1-a)S_{t-1}$$

2. Feature extraction

- **Arousal: log(**alpha)-**log(**beta)
- **Calibration:** IQR of 80 baseline samples to define viability band

2 Modes

Real Mode (The Inspiration)

Controller: Human Participant

Sensor: Muse S EEG Headband

Goal: Test if a person can consciously control their brainwaves to stay within the viability band.

Limitations: "Out of our control." Subject to brain power, hardware accuracy, environmental noise, and muscle artifacts. Impossible to fast-forward time or systematically test different control strategies.

Simulation Mode (The Arena)

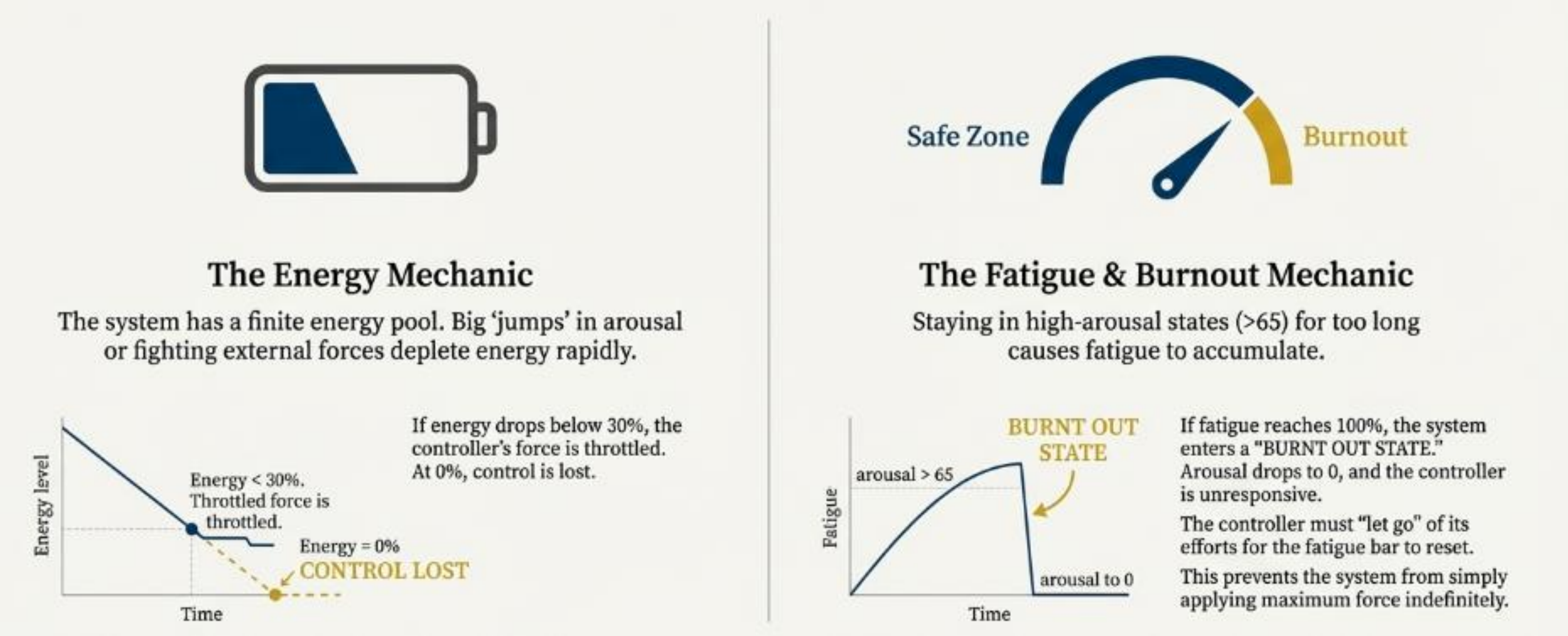
Controller: Digital Algorithm (P or PID)

Sensor: Simulated Data Stream

Goal: Analyze how different digital controllers perform when pushed to their limits by controlled external forces.

Advantages: Allows for systematic testing, control over variables (noise, latency), and exploration of system failure points.

Resource-Constrained Environment



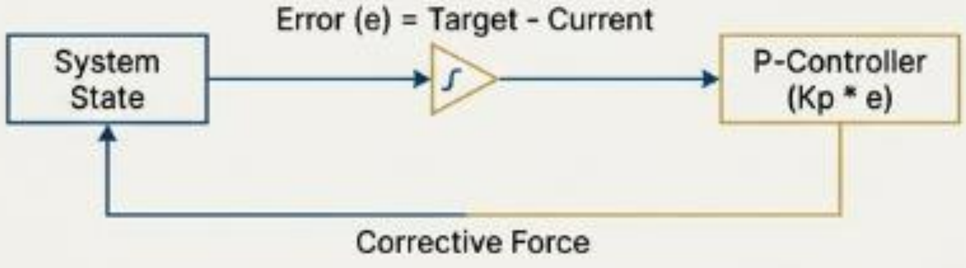
Simple Reacting Controller vs. Adaptive Controller

$$x_{t+1} = x_t + F_{drift} + \underbrace{(F_{controller} \cdot (1 - B))}_{\text{Switched Control}} + F_{threat} + \text{Noise}$$

The P-Contro

The Simple Con

Logic: Calculates
and the target and applies a corrective force proportional to that error.



F _effort[n] = Kp * e[n]

Characteristics:

- Simple, intuitive, and effective in noise-free environments. Prone to failure when faced with complex disturbances.

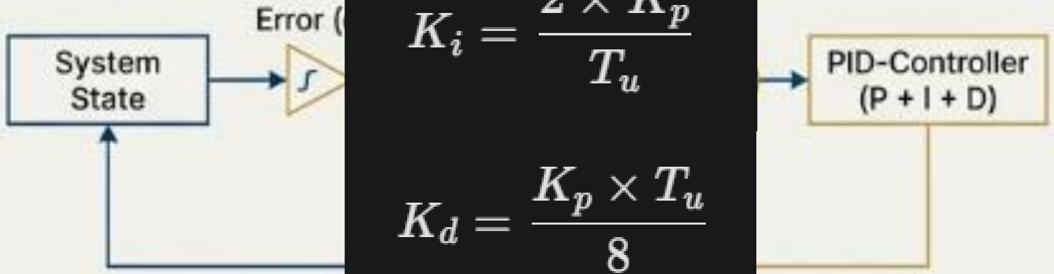
onal-Integral-Derivative)

taking into account the accumulated past error (integral) and the current velocity of the err

$$K_p = 0.60 \times K_u$$

$$K_i = \frac{2 \times K_p}{T_u}$$

$$K_d = \frac{K_p \times T_u}{8}$$



F _PID[n] = Kp*e[n] + Ki*Σe[k] + Kd*(e[n] - e[n-1])

Key Feature: Includes a Ziegler-Nichols (Z-N) closed-loop auto-tuner to find its own optimal parameters, acting like an “adaptive brain.”

The Challenges

Latency: A delay in the control loop.

Noise: Random fluctuations in the sensor signal.

Environmental Forces: A constant external pressure pushing the system off-target.

Combined Forces: All disturbances applied simultaneously.

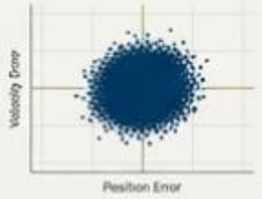
The Metrics

Total Cost (SSE): The cumulative tracking error (Sum of Squared Errors). Lower is better.

Time to Reach Goal: Time until the system stays in the viability band for 3 consecutive seconds.

Energy Spent: Total energy consumed to reach the goal.

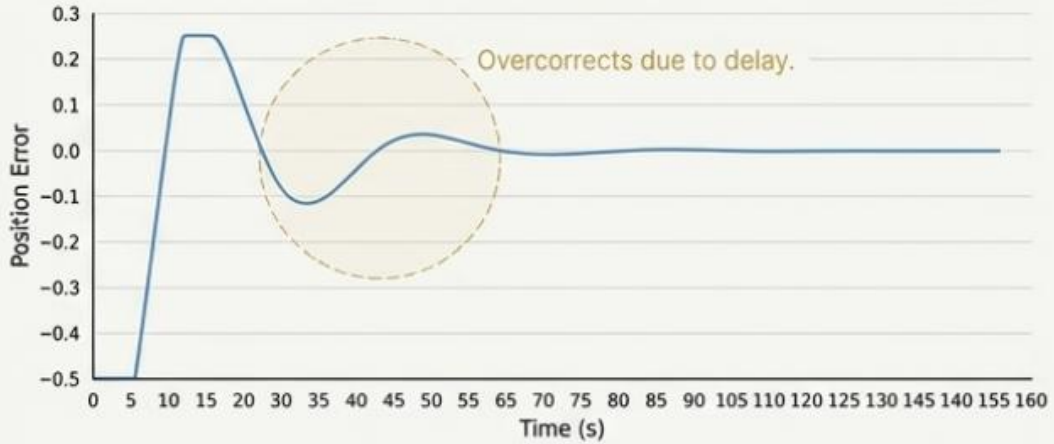
Phase Portrait: A plot of Position Error vs. Velocity Error, used to visualize system stability. A tight cluster indicates stability.



Trials

Trial 1: Latency — The PID Controller Navigates Delays with Precision

P-Controller



Key Stats

Total Cost (SSE): **3.04**

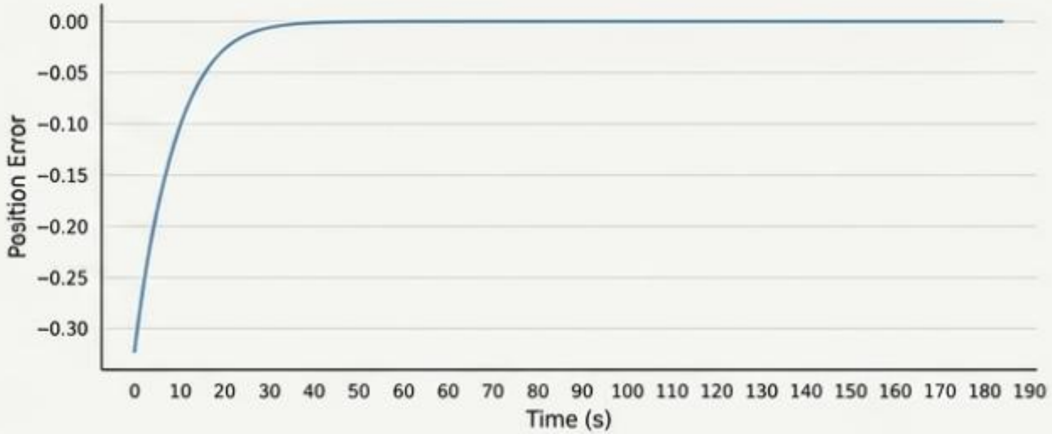
Time to Goal: **7.20 s**

Energy Spent: **14.97%**

Analysis

The Position Error plot shows visible oscillations as the controller overcorrects due to the delay.

PID-Controller



Key Stats

Total Cost (SSE): **0.52 (~6x lower)**

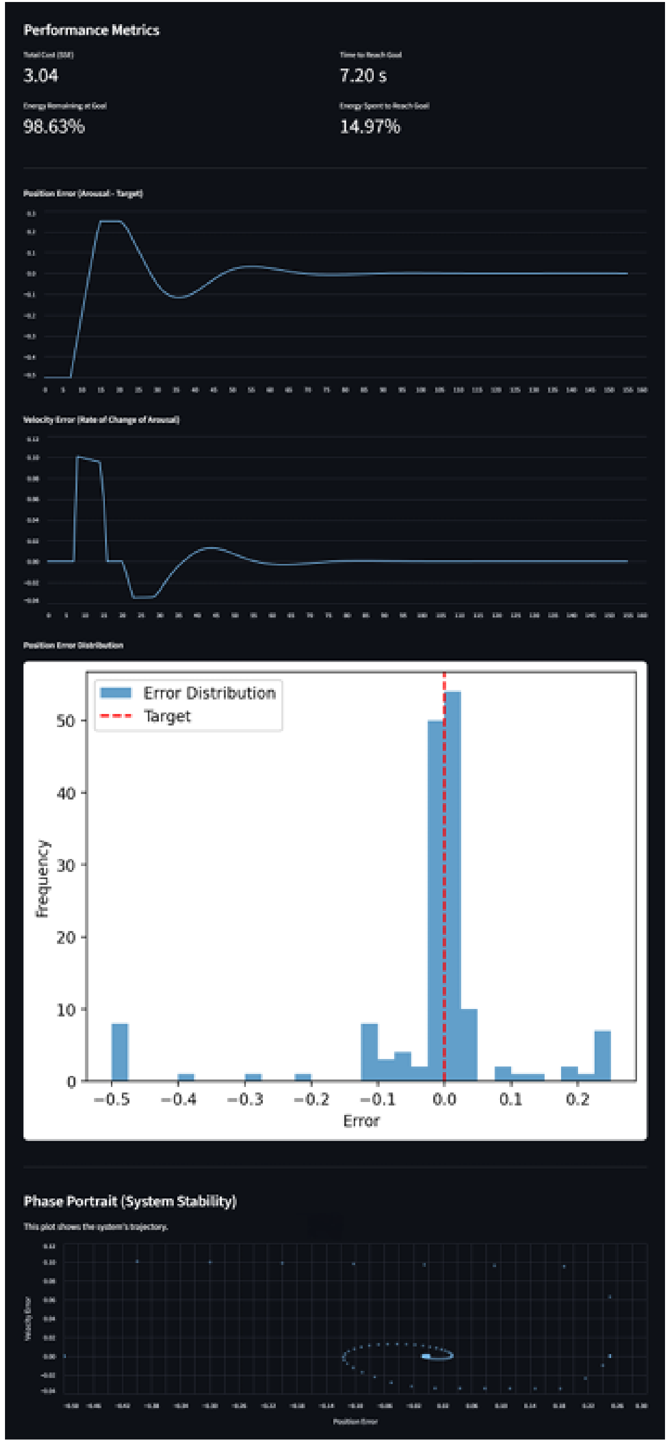
Time to Goal: **5.80 s (Faster)**

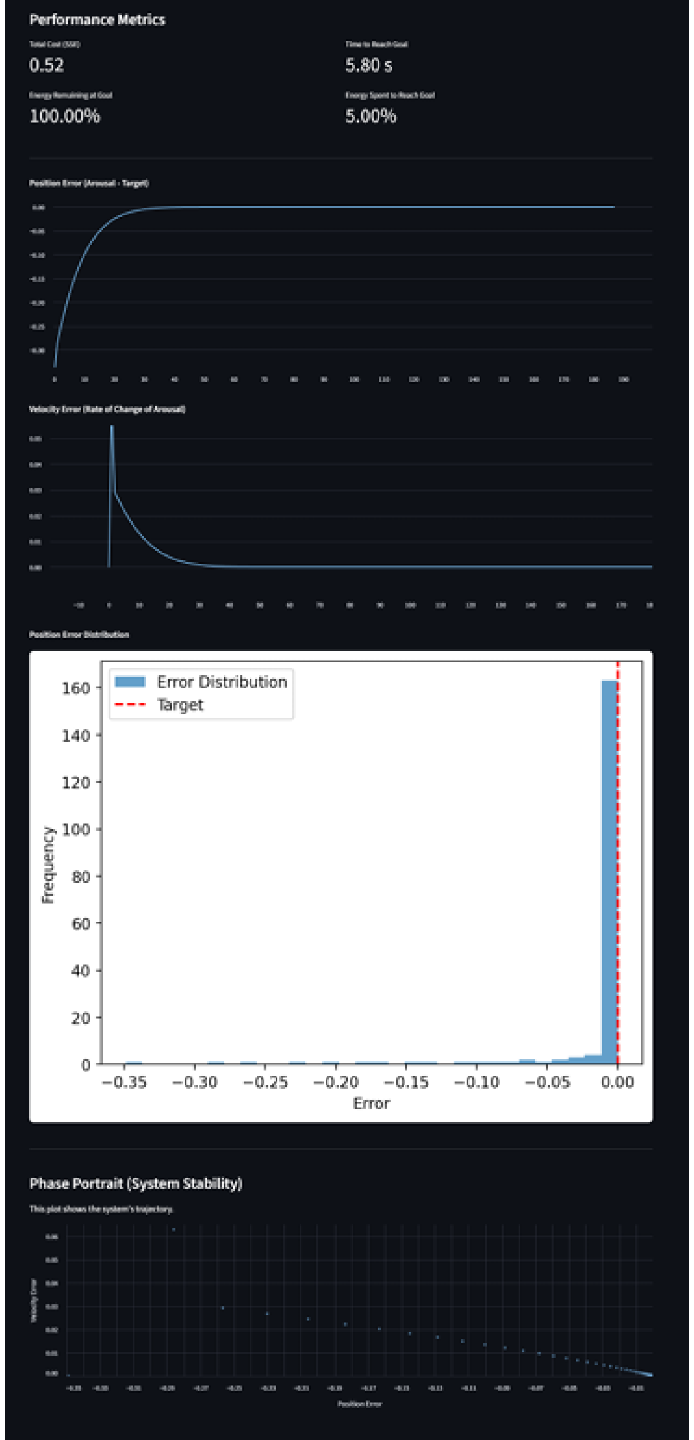
Energy Spent: **5.00% (~3x more efficient)**

Analysis

The Position Error plot shows a smooth, critically-damped approach to the target, completely unaffected by latency.

Latency


Performance Metrics
Total Cost (SSE)
3.04
Time to Reach Goal
7.20 s
Energy Remaining at Goal
98.63%
Energy Spent to Reach Goal
14.97%
Position Error (Arousal - Target)
Velocity Error (Rate of Change of Arousal)
Position Error Distribution
Error Distribution
Target
Frequency
Error
Phase Portrait (System Stability)
This plot shows the system's trajectory.


Performance Metrics
Total Cost (SSE)
0.52
Time to Reach Goal
5.80 s
Energy Remaining at Goal
100.00%
Energy Spent to Reach Goal
5.00%
Position Error (Arousal - Target)
Velocity Error (Rate of Change of Arousal)
Position Error Distribution
Error Distribution
Target
Frequency
Error
Phase Portrait (System Stability)
This plot shows the system's trajectory.

Trial 2: Noise — While Neither Stabilizes, PID Drastically Reduces Error

With high noise (0.2) and a tight viability band, neither controller managed to stay in the goal for 3 consecutive seconds.

P-Controller

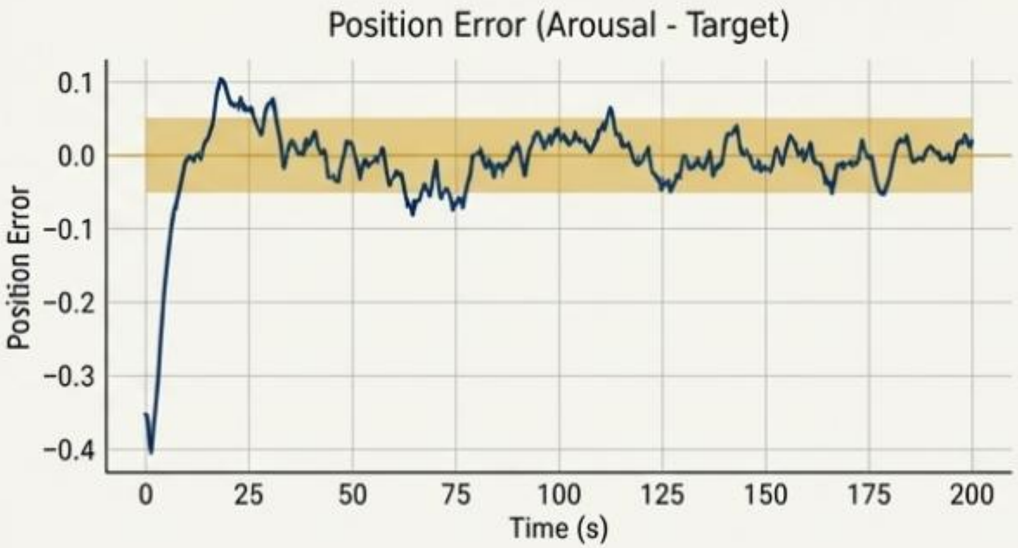
Key Stats

Total Cost (SSE): **7.14**

Analysis

The Position Error graph shows wide, erratic fluctuations far from the target.

PID-Controller



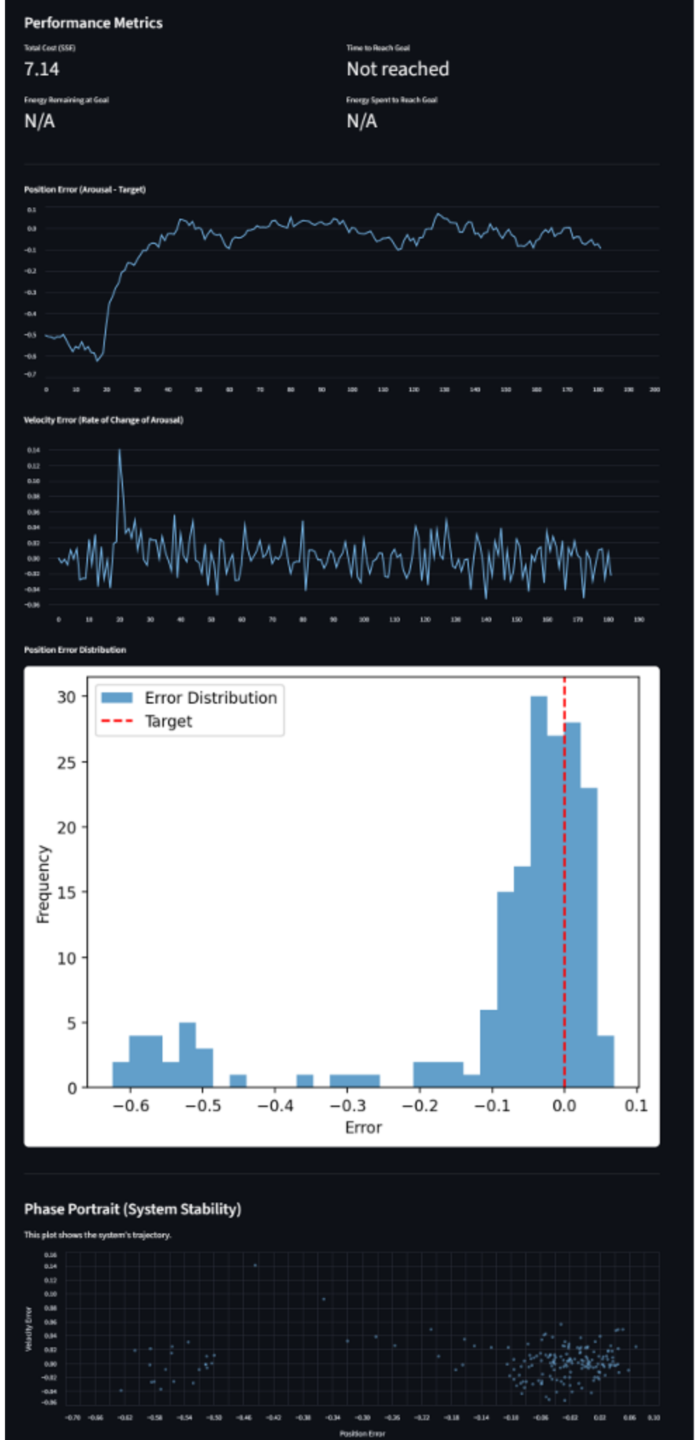
Key Stats

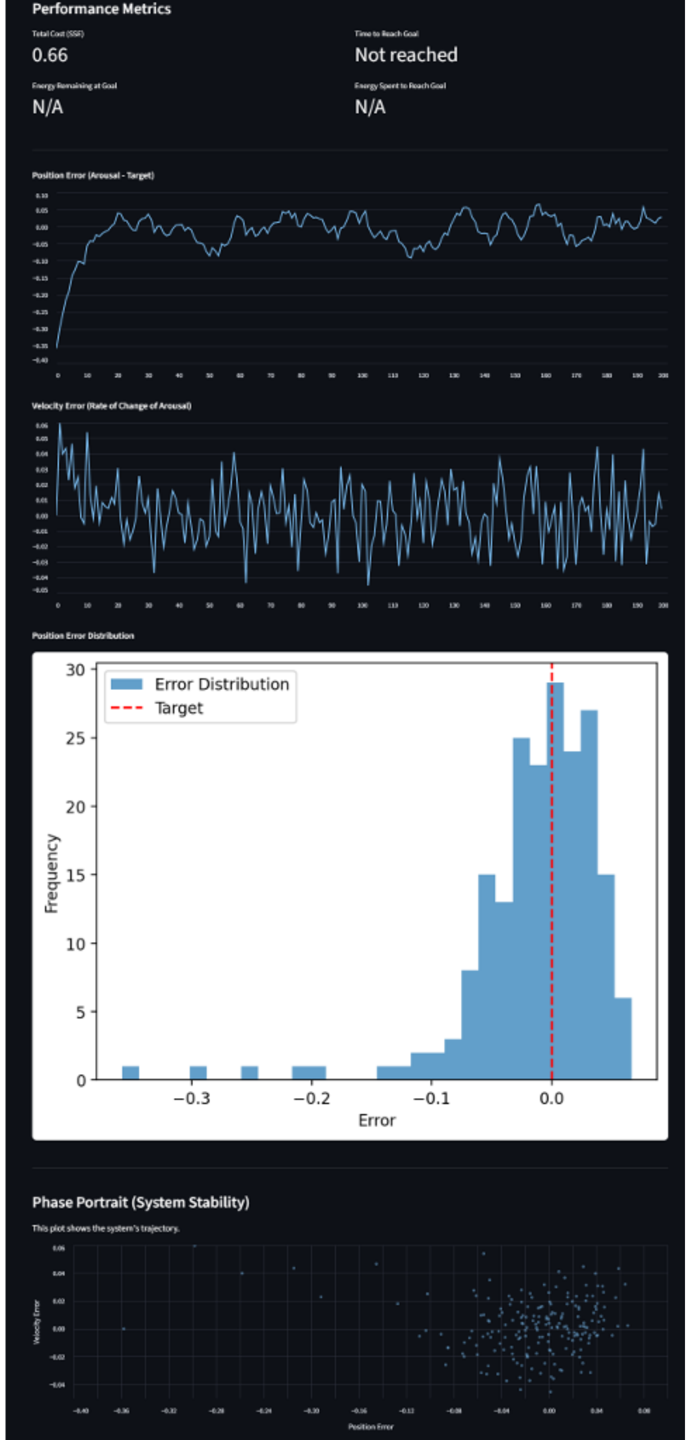
Total Cost (SSE): **0.66**
(Over 10x lower)

Analysis

The error is significantly lower, with the system's position clustered much more tightly around the target, demonstrating superior disturbance rejection.

Noise


Performance Metrics
Total Cost (SSE)
7.14
Time to Reach Goal
Not reached
Energy Remaining at Goal
N/A
Energy Spent to Reach Goal
N/A
Position Error (Arousal - Target)
Velocity Error (Rate of Change of Arousal)
Position Error Distribution
Error Distribution
Target
Frequency
Error
Phase Portrait (System Stability)
This plot shows the system's trajectory.


Performance Metrics
Total Cost (SSE)
0.66
Time to Reach Goal
Not reached
Energy Remaining at Goal
N/A
Energy Spent to Reach Goal
N/A
Position Error (Arousal - Target)
Velocity Error (Rate of Change of Arousal)
Position Error Distribution
Error Distribution
Target
Frequency
Error
Phase Portrait (System Stability)
This plot shows the system's trajectory.

Trial 3: Environmental Force — The P-Controller is Overwhelmed, While PID Converges

An external force of 0.3 pushes the arousal level higher, forcing the controllers to constantly fight back.

P-Controller

Key Stat Total Cost (SSE): 10.30

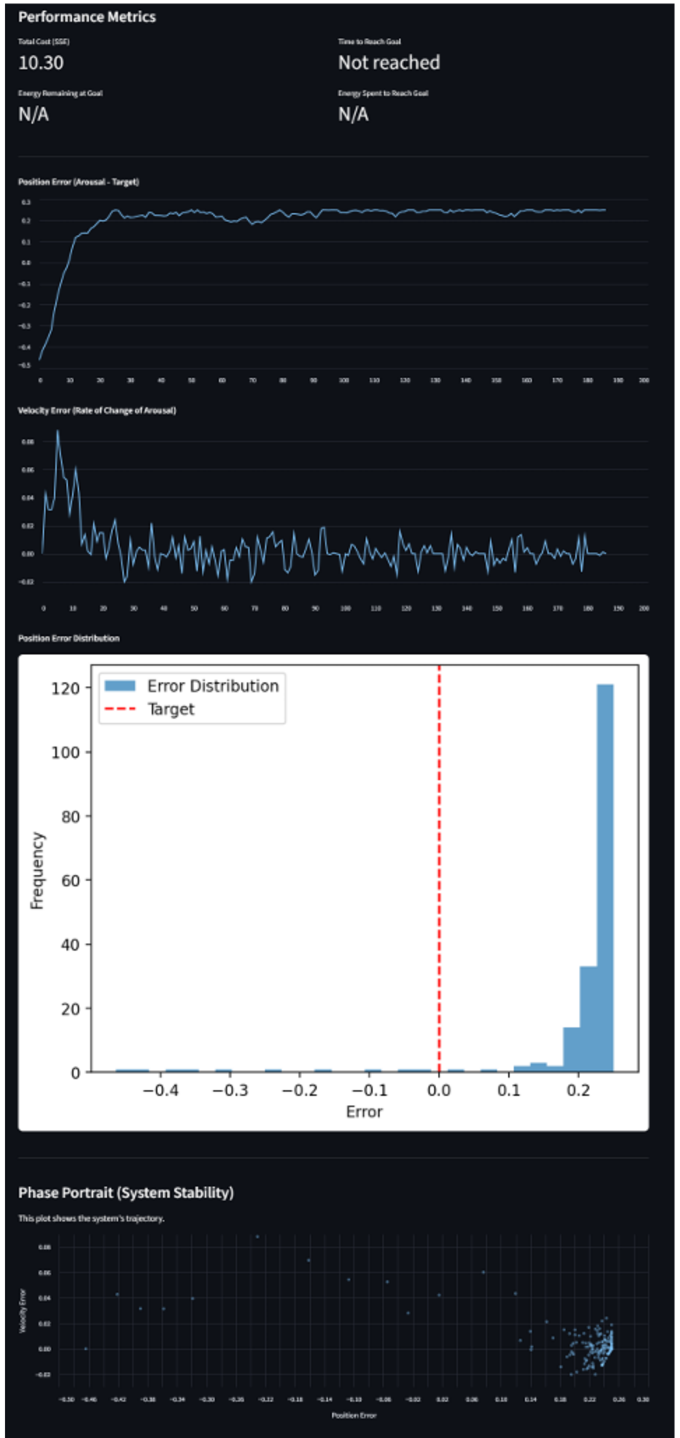
Analysis The controller's gain is not strong enough. It is unable to bring the error to zero, resulting in a large steady-state error.

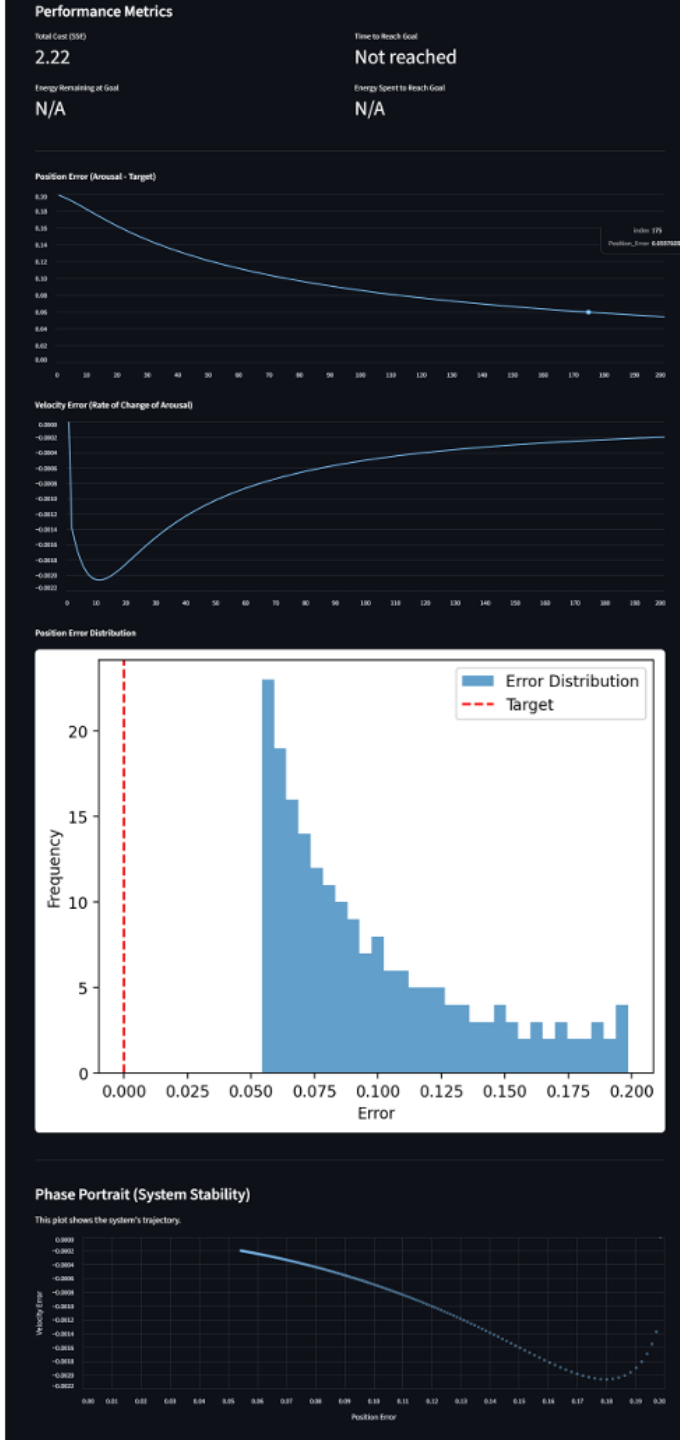
PID-Controller

Key Stat Total Cost (SSE): 2.22 (~5x lower)

Analysis The plot shows a smooth, consistent convergence towards the target. The system methodically eliminates the error over time.

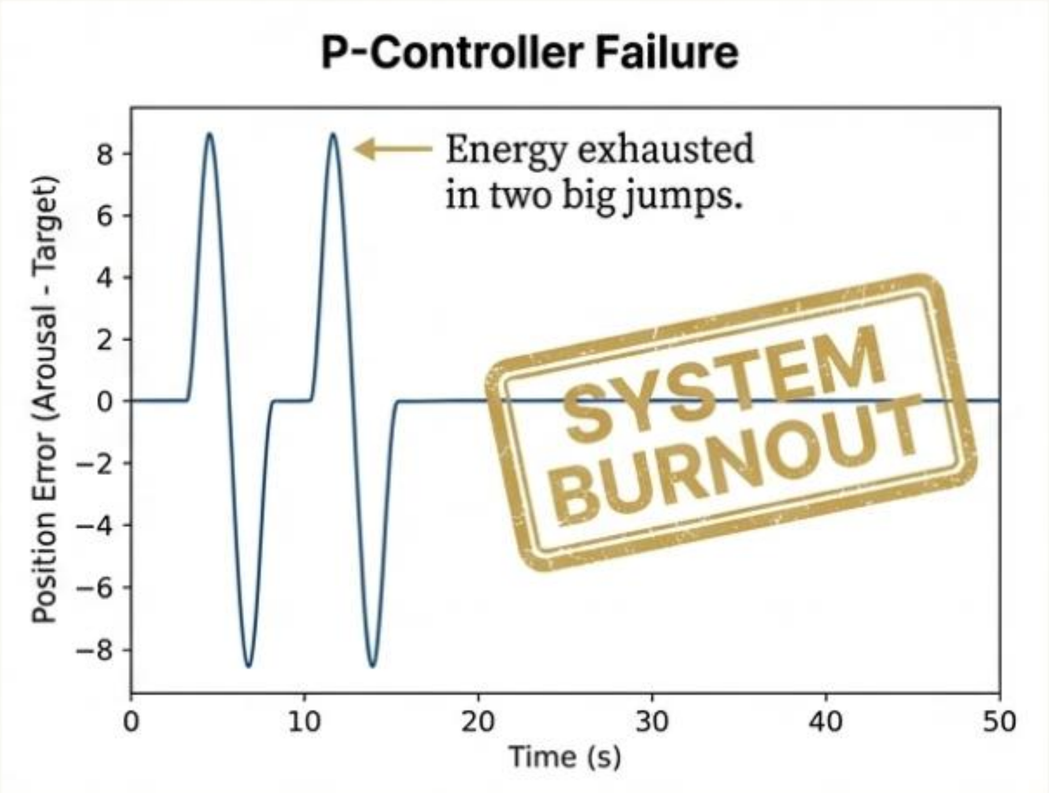
Env


Performance Metrics
Total Cost (SSE)
10.30
Time to Reach Goal
Not reached
Energy Remaining at Goal
N/A
Energy Spent to Reach Goal
N/A
Position Error (Arousal - Target)
Velocity Error (Rate of Change of Arousal)
Position Error Distribution
Error Distribution
Target
Frequency
Error
Phase Portrait (System Stability)
This plot shows the system's trajectory.

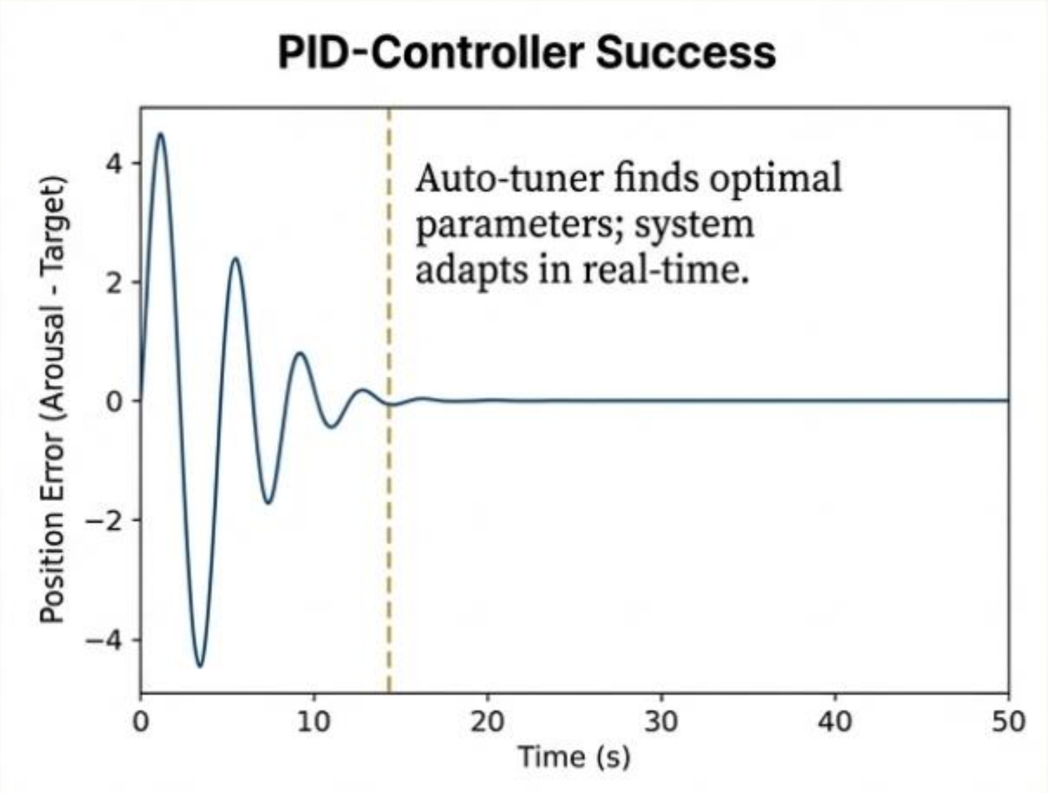

Performance Metrics
Total Cost (SSE)
2.22
Time to Reach Goal
Not reached
Energy Remaining at Goal
N/A
Energy Spent to Reach Goal
N/A
Position Error (Arousal - Target)
Velocity Error (Rate of Change of Arousal)
Position Error Distribution
Error Distribution
Target
Frequency
Error
Phase Portrait (System Stability)
This plot shows the system's trajectory.

The Final Gauntlet: P-Controller Fails and Burns Out, PID Adapts and Succeeds

All forces are combined: Environmental Threat (0.3), Noise (0.02), and Latency (5).



With high gain (kp=1), the P-controller overreacts to the combined disturbances, exhausting its energy resources and resulting in total system failure.



Only the PID-controller successfully stabilizes. Despite costing half its energy, it adapts to the harsh conditions and achieves the goal in 7.10 seconds.

The Verdict is Clear: The PID Controller is Superior in Harsh Environments

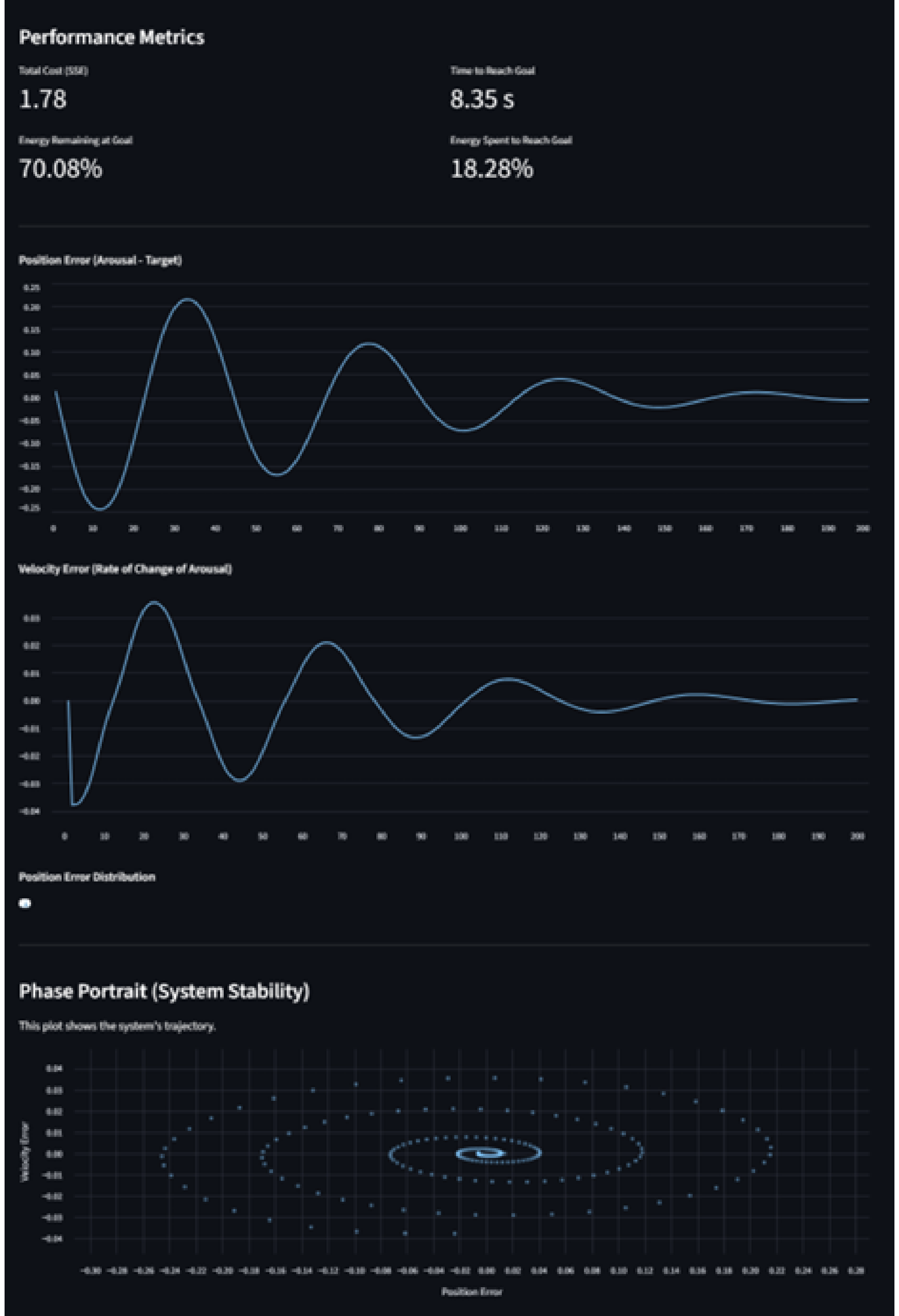
Trial Condition	P-Controller (Result)	PID-Controller (Result)	Key Advantage
Latency	Reached Goal (SSE: 3.04)	Reached Goal (SSE: 0.52)	**6x lower error, 3x more energy efficient**
Noise	Not Reached (SSE: 7.14)	Not Reached (SSE: 0.66)	**>10x lower error**
External Force	Not Reached (SSE: 10.30)	Converging (SSE: 2.22)	**Overcomes steady-state error**
All Forces Combined	**FAILURE (Burnout)**	**SUCCESS (Reached Goal)**	**Robust, Adaptive, Successful**

Across all metrics—Total Cost, Time to Goal, and success under pressure—the PID controller demonstrates vastly superior performance and robustness.

Limitations

- different participants
- no real exploration using EEG mode for this system
- 4-channel EEG consumer grade
- Some artifacts

Bonus


Performance Metrics
Total Cost (SSE)
1.78
Time to Reach Goal
8.35 s
Energy Remaining at Goal
70.08%
Energy Spent to Reach Goal
18.28%
Position Error (Arousal - Target)
Velocity Error (Rate of Change of Arousal)
Position Error Distribution
Phase Portrait (System Stability)
This plot shows the system's trajectory.
Velocity Error
Position Error

Thank you!

- Questions?