Physical Consistency Audit Technical Whitepaper

On Physical Consistency Limits of Discrete-Time Simulation
A Physical Consistency Audit (PCA) of Isaac Sim under Perturbation and Energy Constraints

Abstract

Modern robotics and embodied AI simulation platforms predominantly rely on discrete-time stepping combined with frame-isolated spatial solvers. While this paradigm enables scalability, its implications for physical consistency under perturbations, contact-rich dynamics, and high-frequency interactions remain insufficiently quantified.

In this work, we introduce a **Physical Consistency Audit (PCA)** framework and apply it to NVIDIA Isaac Sim using two minimal, reproducible tests: **Perturbation Robustness Testing** and **Energy Conservation & Numerical Convergence Testing**. These tests quantify deviations from physically expected behavior under default simulator configurations, without solver parameter tuning.

We further demonstrate that an experimental **temporal semantics layer**, implemented as a plugin without modifying the underlying physics solver, significantly reduces these deviations. The results indicate that the observed inconsistencies are not isolated implementation issues, but are structurally linked to the discrete-time, frame-based simulation paradigm itself.

For the Isaac+Oct system, the same simulator and models are used, with an additional temporal update layer enabled via an Isaac Sim extension.

1. Physical Consistency Audit (PCA)

1.1 Motivation

Task success and visual plausibility are insufficient indicators of physical fidelity. Subtle numerical artifacts—especially under perturbations and contact-dominated dynamics—can bias learning signals and accumulate into systematic sim-to-real gaps.

PCA is designed to evaluate **numerical and architectural consistency**, independent of task objectives.

1.2 PCA Definition

A **Physical Consistency Audit (PCA)** evaluates whether a simulator preserves core physical invariants under controlled conditions:

1. **Perturbation Robustness** – bounded response to bounded parameter changes
2. **Energy Consistency** – conservation or monotonic dissipation where physically expected
3. **Numerical Convergence & Boundedness** – absence of sustained oscillations or divergence
4. PCA does **not** assert physical correctness of models; it audits **how simulation evolves over time**.

2. PCA Metrics (Engineering Definitions)

2.1 Perturbation Robust Success Rate (PRS)

$$\mathrm{PRS} = \frac{N_{\text{successful runs}}}{N_{\text{total runs}}}$$

A run is successful if:

- RMS trajectory deviation ≤ threshold
- No NaNs or unbounded states occur

Physical expectation: PRS → 1 under small perturbations.

2.2 RMS Trajectory Error (RMS-TE)

$$\mathrm{RMS} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(\theta(t) - \theta_{\text{ref}}(t))^2}$$

Used to measure sensitivity amplification under perturbation.

2.3 Max Relative Energy Deviation (MRED)

$$\mathrm{MRED} = \max_t \left| \frac{E(t) - E(0)}{E(0)} \right|$$

Evaluated in conservative (zero-damping) systems.

2.4 Energy Jitter Index (EJI)

$$\mathrm{EJI} = \frac{\sigma(\Delta E)}{\mathbb{E}(|E|) + \epsilon}$$

Captures high-frequency, step-to-step energy fluctuations (“ECG-like jitter”).

2.5 Tail Velocity Average (TVA)

$$\mathrm{TVA} = \frac{1}{K} \sum_{t=T-K}^{T} |\omega(t)|$$

Evaluates numerical convergence in dissipative systems.

2.6 Boundedness Check (BC)

Binary check for:

- Divergence
- NaNs
- Physically implausible values

Failure triggers a score penalty.

3. PCA Score (0–100)

PCA Score is a **reporting interface**, not a new metric.

3.1 Normalization

```
PRS_norm   = clamp(PRS / 0.95, 0, 1)
RMS_norm   = exp(-RMS / RMS_ref)
MRED_norm = exp(-MRED / 0.02)
EJI_norm   = exp(-EJI / 0.005)
TVA_norm   = exp(-TVA / 0.01)
```

3.2 Aggregation

```
PCA_raw =
    0.25 * PRS_norm +
    0.20 * RMS_norm +
    0.20 * MRED_norm +
    0.20 * EJI_norm +
    0.15 * TVA_norm
```

If boundedness violated:

```
PCA_raw *= 0.7
```

4. Experimental Results

System	PCA Score
Isaac Sim (default)	48–62
Isaac Sim + Temporal Plugin	85–93

All tests were performed **without solver tuning or timestep reduction**.

5. Interpretation

The magnitude and persistence of deviations suggest structural limitations of frame-isolated discrete-time simulation under nonlinear coupling, rather than isolated implementation defects.

6. Implications for Embodied AI

Learning systems trained on numerically inconsistent dynamics may exploit artifacts rather than physics, limiting real-world transfer despite large-scale training.

7. Limitations

- Plugin is experimental
- Results are scenario-dependent
- PCA complements, not replaces, model validation

8. Conclusion

Physical consistency under perturbation and contact-rich dynamics can—and should—be quantitatively audited. PCA provides a reproducible framework to do so.