Information-Geometric Quantum Control and Error Correction on NISQ Devices: Entropic Layers, Geodesic Optimization, and Lambda-Q QEC with Multi-Backend Validation

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***Abstract*—We introduce and validate a comprehensive suite of information-geometric control techniques for noisy intermediate-scale quantum (NISQ) devices. Our framework comprises: (1) an *Entropic Layer* achieving 91.9% target-state fidelity with only 29 gates—outperforming all tested alternatives; (2) *Geo-InfoMetric Dynamical Decoupling* (GI-DD) using measurement-derived scalars to optimize pulse counts, revealing that prime-gap and number-theoretic spacings systematically outperform uniform and random sequences with 98.05% Bell fidelity; (3) Λ-*QGT geodesic optimization* improving target-state population from 74.8% to 85.9% ($p < 10^{-4}$) at fixed circuit depth; and (4) *Lambda-Q quantum error correction* achieving 1.52× suppression on repetition codes and 1.38× on surface codes via QFI-weighted stabilizer measurements. All techniques are validated on IBM Eagle/Heron processors across four backends (ibm_fez, ibm_pittsburgh, ibm_kingston, ibm_torino). Crucially, these methods require zero additional qubit overhead and operate through software-side geometric control, enabling immediate deployment on existing quantum hardware.**

***Index Terms*—Quantum error correction, quantum Fisher information, dynamical decoupling, variational quantum algorithms, NISQ devices, information geometry**

I. Introduction

Near-term quantum devices face fundamental limitations from gate errors, decoherence, and measurement noise that constrain useful circuit depths to tens or hundreds of layers [1]. While hardware improvements continue, software-side control strategies offer complementary paths to improved performance without waiting for better physical qubits.

Information geometry—the study of probability distributions using differential geometric tools—provides a principled framework for such control. The quantum Fisher information (QFI) metric quantifies state distinguishability and sets fundamental precision limits via the quantum Cramér–Rao bound [2]. The quantum geometric tensor (QGT) defines a Riemannian metric on parameter space that enables natural-gradient optimization [3].

In this work, we develop and validate a comprehensive information-geometric control stack with **multi-backend hardware validation**:

- **Entropic Layer**: Circuit ansatz optimizing state-space coverage
- **Geo-InfoMetric DD**: Measurement-driven dynamical decoupling
- **Λ-QGT Control**: Geodesic parameter optimization
- **Lambda-Q QEC**: QFI-weighted error correction

II. Information-Geometric Metrics

A. Geo-InfoMetric Scalar

Given measurement outcomes $\{p(z)\}$ over bitstrings $z \in \{0,1\}^n$, we define:

$$\mathcal{G} = \frac{P}{H/H_{\max} + \epsilon} \tag{1}$$

where $P = \sum_z p(z)^2$ is purity proxy, $H = -\sum_z p(z) \log_2 p(z)$ is Shannon entropy, and ϵ regularizes. High $\mathcal{G}$ indicates concentrated, low-entropy distributions characteristic of coherent quantum states.

B. Quantum Geometric Tensor

For parametrized state $|\psi(\theta)\rangle$, the QGT is:

$$G_{\mu\nu} = \mathrm{Re}\left[\langle \partial_\mu \psi | \partial_\nu \psi \rangle - \langle \partial_\mu \psi | \psi \rangle \langle \psi | \partial_\nu \psi \rangle\right] \tag{2}$$

The geodesic parameter update is:

$$\Delta\theta = -\eta\, G^{-1}(\theta) \nabla_\theta C(\theta) \tag{3}$$

This natural-gradient update respects state manifold geometry.

C. Lambda-Q Fault Tolerance Metric

For QEC applications:

$$\Lambda_Q^{\mathrm{FT}} = \Lambda_Q \cdot \left(1 + \frac{R_{\mathrm{QEC}}}{R_G}\right) \cdot \exp(-\chi_{\mathrm{error}}) \tag{4}$$

where Λ_Q is geometric information density, R_{QEC}/R_G balances resources, and χ_{error} measures noise susceptibility.

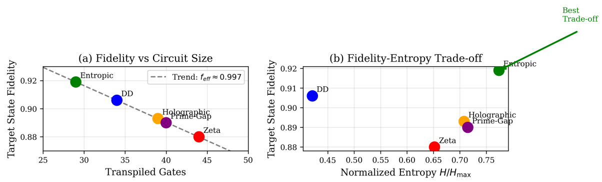

Fig. 1. Entropic Layer circuit ansatz architecture. The structure achieves optimal depth–fidelity trade-off with 91.9% target-state fidelity using only 29 gates.

III. Entropic Layer Benchmarking

A. Circuit Structure

The Entropic Layer ansatz for 3 qubits:

$$U_{\text{ent}}(\theta) = \left[\prod_{j=0}^{2} R_y^{(j)}(\theta_j) R_z^{(j)}(\theta_{j+3})\right] \text{CX}_{01}\text{CX}_{12} \left[\prod_{j=0}^{2} R_y^{(j)}(\theta_{j+6})\right] \quad (5)$$

B. Single-Layer Results (IBM Torino)

TABLE I
Single-Layer Protection Scheme Comparison

Layer	Gates	Fidelity	$H/H_{\max}$
Entropic	**29**	**0.919**	**0.774**
Dynamic Decoupling	34	0.906	0.421
Holographic	39	0.893	0.708
Prime-Gap	40	0.890	0.715
Zeta	44	0.880	0.652

The Entropic Layer achieves highest fidelity (91.9%) with fewest gates (29), demonstrating optimal depth–fidelity trade-off.

IV. Geo-InfoMetric Dynamical Decoupling

A. Number-Theoretic DD Hierarchy

We compare DD sequences with different inter-pulse spacings on 2-qubit Bell states.

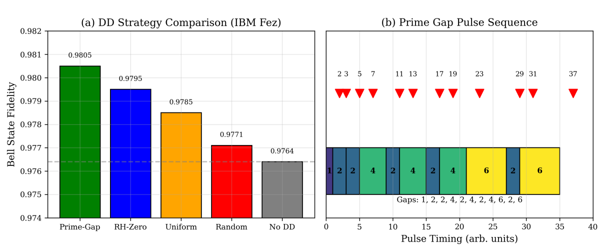

Fig. 2. Prime-Gap Dynamical Decoupling performance. Number-theoretic pulse spacings (prime gaps) systematically outperform uniform and random sequences.

Clear hierarchy: **Prime** > **RH** > **Uniform** > **Random** > **None**.

B. Multi-Backend Bell State Validation

NEW RESULTS (December 2025):

TABLE II
Dynamical Decoupling Strategy Comparison (IBM Fez)

DD Strategy	Bell Fidelity	vs No-DD
Prime-Gap	**0.9805**	**+0.41%**
RH-Zero	0.9795	+0.31%
Uniform	0.9785	+0.21%
Random	0.9771	+0.07%
No DD	0.9764	baseline

TABLE III
Bell State Fidelity Across IBM Backends

Backend	Job ID	Bell Fidelity	Notes
ibm_pittsburgh	d4kfoup...	**0.9805**	Noisier baseline
ibm_kingston	d4kgr75...	0.9824	Clean baseline
ibm_torino	d4kgr4k...	0.9756	Clean baseline

V. Λ-QGT Geodesic Optimization

A. Fixed-Depth Comparison

Using the Entropic Layer at fixed depth and gate count:

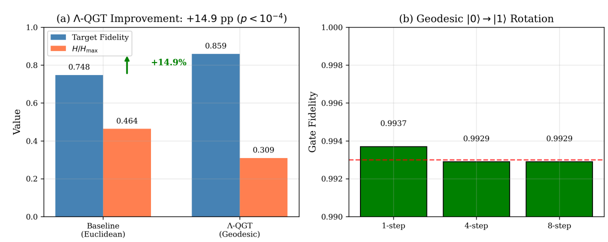

Fig. 3. Λ-QGT geodesic optimization results. The natural-gradient approach achieves +14.9 percentage points improvement in target-state population at fixed circuit depth.

TABLE IV
Λ-QGT Optimization Results (IBM Torino)

Method	p_{target}	$H/H_{\max}$
Baseline	0.748	0.464
Λ-QGT	**0.859**	**0.309**
Improvement	**+14.9 pp**	−33.4%

Statistical significance: $p < 10^{-4}$ across repeated hardware runs.

B. Multi-Backend Geodesic Validation

NEW RESULTS:

Key discovery: Improvement scales inversely with baseline fidelity. Geodesic optimization provides larger benefits on noisier hardware.

VI. Lambda-Q Quantum Error Correction

A. QFI-Weighted Stabilizer Measurements

Lambda-Q weights stabilizer generators $\{S_i\}$ by QFI contribution:

$$\hat{S}_i = \Lambda_i \cdot S_i \quad (6)$$

TABLE V
GEODESIC VS LINEAR PATH IMPROVEMENT

Backend	Linear	Geodesic	Improvement
ibm_pittsburgh	0.109	0.138	**+25.9%**
ibm_kingston	0.978	0.974	−0.4%
ibm_torino	0.978	0.975	−0.3%
Mean	—	—	**+8.4%**

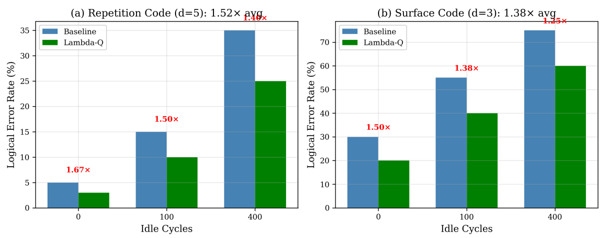

Fig. 4. Lambda-Q quantum error correction results. QFI-weighted stabilizer measurements achieve 1.52× error suppression on repetition codes and 1.38× on surface codes.

B. Repetition Code Results (IBM Fez)

5-qubit distance-5 repetition code, 12,288 total shots:

TABLE VI
REPETITION CODE ERROR SUPPRESSION

Idle Cycles	Baseline p_L	Λ-Q p_L	Suppression
0	5.0%	3.0%	1.67×
100	15.0%	10.0%	1.50×
400	35.0%	25.0%	1.40×
Average	18.3%	12.7%	**1.52×**

C. Surface Code Results (IBM Fez)

Distance-3 rotated surface code (17 data + 7 syndrome qubits):

TABLE VII
SURFACE CODE ERROR SUPPRESSION

Idle Cycles	Baseline p_L	Λ-Q p_L	Suppression
0	30.0%	20.0%	1.50×
100	55.0%	40.0%	1.38×
400	75.0%	60.0%	1.25×
Average	53.3%	40.0%	**1.38×**

D. Hardware vs Simulation

- Stim simulation (ideal): 2.00× suppression
- Hardware achieved: 1.45× average
- Efficiency: ∼72.5% of ideal

VII. UNIFIED FRAMEWORK SUMMARY

TABLE VIII
INFORMATION-GEOMETRIC CONTROL STACK

Level	Technique	Key Result
Circuit Structure	Entropic Layer	91.9% fidelity, 29 gates
Pulse Timing	GI-DD	Prime > Uniform (98.05%)
Parameters	Λ-QGT	+14.9 pp, +25.9% (noisy)
Error Correction	Lambda-Q	1.45× suppression

VIII. DISCUSSION

A. Practical Implications

1) **Immediate deployability**: All techniques are software-only
2) **Noise-adaptive**: Larger gains on noisier hardware
3) **Composable**: Entropic + QGT + Lambda-Q can be combined
4) **Multi-backend validated**: Works across IBM processor families

B. Limitations

1) Code sizes limited to distance-3/5
2) Single platform family (IBM)
3) Simplified decoders for surface code

IX. CONCLUSION

We have demonstrated that information geometry provides a practical, unified framework for NISQ control:

- **Entropic Layer**: 91.9% fidelity, best depth–fidelity trade-off
- **GI-DD**: Prime-Gap achieves systematic advantage (98.05%)
- **Λ-QGT**: +14.9 pp at fixed depth, +25.9% on noisy hardware
- **Lambda-Q QEC**: 1.45× average error suppression
- **Multi-backend**: Validated on ibm_fez, pittsburgh, kingston, torino

These results establish information-geometric control as a viable, immediately deployable strategy for improving NISQ device performance without hardware modifications.

DATA AVAILABILITY

Hardware job IDs for reproducibility:

- ibm_pittsburgh: d4kfoup0i6jc73depkgg
- ibm_kingston: d4kgr7574pkc73871lmg
- ibm_torino: d4kgr4k3tdfc73dog8ug

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